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PHOSPHORUS REMOVAL AND DISPOSAL FROM MUNICIPAL WASTEWATER

Cecil H. Connell

Texas University

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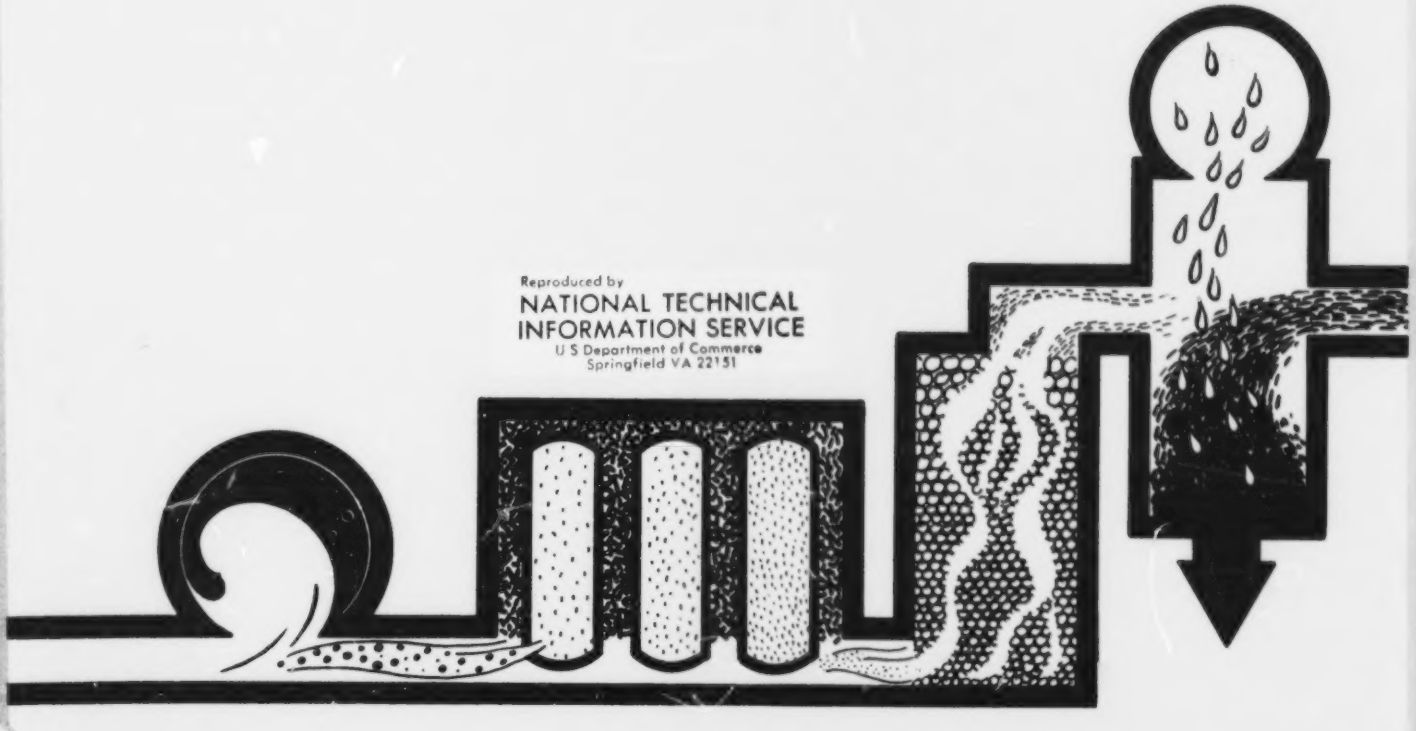

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27 Abstract Phosphorus removal was implemented at the full-scale, 1 mgd, Texas City, Texas Activated Sludge Plant. Over a two-year period, several techniques were investigated. Control of the plant operations to enhance biological removal of phosphorus was not a reproducible process. The most efficient means of controlling phosphorus was by the use of iron salts added to the raw wastewater or primary effluent. Aluminum salts were slightly less effective. All aspects of plant operation were investigated, such as excess sludge production and drainability of digested sludge. Estimates of the operating costs associated with phosphorus removal are presented.

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PHOSPHORUS REMOVAL AND DISPOSAL FROM MUNICIPAL WASTEWATER

by

University of Texas Medical Branch
Galveston, Texas 77550

for the

ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

Biological and chemical precipitation of phosphorus was studied in a 0.7 MGD activated sludge plant.

Biological precipitation removed 0-70% of phosphorus. Near complete mix aeration, plus variations in COD and P loadings, precluded holding solids, COD and DO at levels favorable to P enrichment of solids. With biological uptake of P there was magnesium-phosphorus co-enrichment of solids at mol ratios of about 0.3/1, Mg/P.

Injection of Fe(II) to raw influent at doses of 1.3/1 - 1.6/1, Fe/P, for 80-90% removal, at chemical cost of $0.32/lb of P removed was the most feasible treatment. Dosage efficiency for Fe(II) to primary effluent was slightly less; for Fe(III) to primary effluent appreciably less; for Fe(III) to raw influent, least.

Doses of Al(III) at 1.6/1 to 1.8/1, Al/P, to primary effluent removed 80% P, but to raw influent, only 70%.

Dosage efficiency dropped significantly in attempts to raise removal above 90% by iron, or above 80% by aluminum.

Injection of a polyelectrolyte to aeration effluent raised removal from 80% to above 90% for a 2.5/1, Al/P, dose of Al(III).

Within the 70% over-capacity of the digester and drain beds the iron-phosphate sludge digested and dewatered effectively. About 150% over conventional design capacity was indicated for the alumina-phosphate sludge.

Whether iron or aluminum was used, phosphorus remained insolubilized through digestion.

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CONTENTS

	Page
INTRODUCTION	1
Objective	1
Treatment Schemes	1
Premises for Treatment Schemes	1
TREATMENT PLANT	9
AUXILIARY FACILITIES	11
SAMPLING AND ANALYTICAL PROCEDURES	12
DEMONSTRATION PROCEDURES AND RESULTS	13
Removal by Activated Sludge, No Added Cations	13
Removal and Disposal of Phosphorus From Digester Liquor	23
Utilization of Iron in Primary and Aeration Processes	28
Limited Lime to Return Sludge, Then Raw Influent	39
Aluminum Cloride to Raw Influent and Primary Effluent	42
DISCUSSION	48
Removal by Activated Sludge, No Added Cations	48
Removal of Phosphorus from Digester Liquor	60
Removal and Disposal of Phosphorus by Use of Iron	64
Removal and Disposal of Phosphorus by Use of Aluminum Cloride	73
SUMMARY AND CONCLUSIONS	78
ACKNOWLEDGMENTS	85
REFERENCES	86
TABLES	
FIGURES	

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INTRODUCTION

OBJECTIVE

In studies, 1967-1969, at a 0.7 MGD (2650 cu m) activated sludge plant, Texas City, Texas,the objective was to demonstrate by two treatment schemes the effectiveness, feasibility and costs of biological and chemical processes for removal and disposal of phosphorus.

TREATMENT SCHEMES

Treatment Scheme Number One

This was to adjust operation parameters for biological precipitation of solids of highest possible phosphorus content. Anaerobically digest the solids. Chemically precipitate released phosphorus from the digester liquor. Drain and dry the digested and reprecipitated solids on sand beds for land disposal or utilization.

Treatment Scheme Number Two

This was the same as the first except that biological precipitation of phosphate solids would be supplemented by chemical precipitation in primary and aeration processes.

PREMISES FOR TREATMENT SCHEMES

Biological Precipitation

Biological precipitation and removal of phosphorus is limited: first, by organic material and nutrients for building cell solids; second, by the phosphorus incorporated into cell solids, i.e., the 1 to 2% requirement for cell production during exponential growth (1,2,3,4), or up to 5 - 7% (5,6) including "luxury" (?), "overplus" (7,8) or "volutin" (9) storage of polyphosphate under nutritional imbalance unfav-

orable to cell growth; third, by instability of high-phosphate solids, i.e., release of phosphorus at low pH (2,10) or with deficiency of oxygen, or surplus of substrate food (2,6,11); and fourth, by the particle size and agglomerated or bioflocculated state (12), i.e., their settleability or floatability.

The high phosphorus removal at San Antonio, Texas, observed by Vacker, et. al., (6), and by Witherow, Priesing, et. al. (11, 13), and at other activated sludge plants observed by Levin and Shapiro and by Witherow and Priesing, is attributed by Vacker, et. al., to biological enrichment; by Levin and Shapiro to "luxury" metabolic uptake; by Priesing (13), to sorption by cells; and by Menar and Jenkins (14) to phosphorus enrichment of the sludge by calcium phosphate precipitation.

There were observations common to several of the investigations (2,6,10,11,13). The rapid and almost complete uptake of phosphorus was toward the end of the log growth substrate utilization phase into the bioflocculation endogenous phase, with dissolved oxygen approaching or exceeding 1 mg/l. Higher DO levels promoted phosphorus uptake, but if extended, released phosphorus by endogenous lysing of cells. There was release of cell enrichment of phosphorus when aeration was withdrawn for considerable time, e.g., with slow movement of sludge through secondary clarifiers; also, when there was reloading with substrate food, e.g., with mixing of plant influent with return sludge. Effective removal of a phosphorus load was attained most readily by batch treatment, e.g., in bench-scale tests; or under "plug" flow, e.g., in the long aeration tanks of the San Antonio, Milwaukee and Baltimore plants, wherein complete substrate utilization could be approached and adequate bioflocculation attained. And, high degree of phosphorus removal was realized

only when there was non-return of high phosphorus digester liquors.

At the Texas City Plant #2, it was evident that, even with the wide diurnal variations in plant flow and COD and phosphorus loadings, an approach to plant-scale batch treatment was limited. The short length aerator coupled with turbulent aeration produced a flow-through pattern much closer to complete mix than to plug flow. And the return of high phosphorus digester liquor precluded high degree phosphorus removal. However, pre-demonstration observations revealed several favorable treatment results. Influent COD and phosphorus loads and rates were such, that sufficient high-phosphorus solids might be built to remove 80-90% of the phosphorus. COD to aeration solids loadings and aeration, were readily controlled for effective substrate utilization and bio-flocculation. Sludge withdrawal from secondary clarifiers was sufficiently rapid to prevent anoxic release of phosphorus enrichment. There was phosphorus enrichment of aeration solids. As high as 5% phosphorus was observed. As low as 2 mg/l soluble phosphorus in the plant effluent was observed for short periods. In bench-scale batch treatment, 70-80% of phosphorus was removed from portions of primary effluent aerated with 2000 mg/l of return sludge solids. There was occasional one-day through-plant removal of more than 30% of the phosphorus load, even though high phosphorus digester liquor was being recycled.

Therefore, treatment scheme number one was projected for demonstration of maximum possible removal of phosphorus by biological precipitation, after chemical precipitation of phosphorus from return digester liquor.

Chemical Precipitation

For chemical precipitation of phosphate from wastewater, lime, and the salts of iron and aluminum have been the chemicals of choice for process development and practice.

Use of Lime.--Rudolfs (15,16), (1947), Sawyer (17), (1952), Karanik and Nemerow (18), (1965), Rand and Nemerow (19), (1965), Buzzell and Sawyer (20), (1966), and Albertson and Sherwood (21), (1967) have demonstrated effectiveness and lime requirements for removal of phosphorus from raw wastewater; and Owen (22), (1953), Malhorta, Lee and Rohlich (23), (1964) and Wuhrman (24), (1964) for removal from secondary effluents. There were common observations. Phosphate precipitation was pH dependent. Reduction of phosphorus to below 1 mg/1, or removal of more than 90% of a 10 mg/1 phosphorus load, required that pH be raised to above 10. High alkalinity consumed major proportions of lime doses, and entailed production of large quantities of solids. Menar and Jenkins (14), (1967) demonstrated precipitation of calcium phosphate from high calcium wastewaters, with no added lime, through prolonged aeration for stripping out carbon dioxide, thus raising the pH level.

The forms of phosphate precipitates and the mechanisms of reactions are not fully known. Owen (22) presented the results of his studies on a functional assumption that phosphorus was precipitated as calcium tribasic phosphate. Stumm (25) has stated that in the alkaline pH range hydroxylapatite, $Ca_{10}(PO_4)_6(OH)_2$, is the only stable phosphate phase. Clesceri (16) reports that "colloidal chemical studies have indicated that at pH 11, the predominant calco-phosphate compound is hydroxylapatite, which may be mainly microcrystalline particles and, therefore, somewhat

difficult to sediment." Johnson (26), (1964) states "In the cold lime softening process phosphates are efficiently removed by adsorption on the precipitated lime sludge."

The simplest of chemical models for describing phosphate precipitation in secondary effluents by lime treatment would include the following ion components: Ca^{++}, Mg^{++}, $(HCO_3)^-$, $(CO_3)^=$, $(PO_4)^{\equiv}$ and $(OH)^-$. In treatment of raw wastewater, polyphosphates and organic phosphorus would have to be considered. In treatment of digester liquor the nitrogenous compounds, acidity, and solids components add to the complexity.

However, studies of mechanisms were not within the scope of the process development demonstrations at the Texas City #2 plant. Complexities of reactions were recognized. The approach was emperical. Within the best understanding of relevant information, incremental doses of chemicals were added to selected wastewater streams. Evaluations were made for feasible applications of processes demonstrated.

Pre-demonstration bench-scale studies confirmed pH dependency and lime requirements observed by other investigators, and pointed to objectives and procedures for plant-scale demonstrations. Under treatment scheme for reducing the phosphorus content of digester liquor before recycling it to the activated sludge process, the liquor was to be treated with the minimum of lime required to reduce phosphorus to below about 10 mg/l, with production of least possible amount of solids of best dewaterability. Under treatment scheme number two, for supplementing uptake of phosphorus by primary and aeration solids, precipitation by lime was to be tested at two injection points. First, lime was to be dosed to the return sludge stream, sufficient to induce incipient precipitation of calcium phosphate, and sufficient to raise calcium content

and pH to levels favorable for augmenting uptake of phosphorus by activated sludge solids. Then, second, lime was to be dosed to the raw influent, sufficient for partial removal of phosphorus in primary units, with carry-over of soluble and precipitated calcium into aeration units, potentially favorable to continuing precipitation of phosphate.

Use of Iron and Aluminum.-- Sawyer (17) in 1952 proposed the use of iron and aluminum salts for removal of phosphorus from wastewater. The following have been used in treatment of raw wastewater: ferric chloride, aluminum sulfate, and sodium aluminate by Sawyer (1952); aluminum sulfate by Curry and Wilson (27), (1955), by Neil (28), (1957), and by Rand and Nemerow (19), (1965); and ferrous sulfate and ferrous chloride by Wukash (29), (1967). The following have been used for tertiary treatment of secondary effluents: ferrous, ferric and aluminum sulfate by Lea, Rohlich and Katz (30), (1954); aluminum sulfate by Mahlorta, Lee and Rohlich (23), (1964), and by Culp and Slechta (31); and ferric chloride by Wuhrman (24), (1964). The following have been used for augmenting uptake of phosphorus by aeration solids: ferric chloride by Thomas (32), (1962) and by Wuhrman (24), (1964); aluminum sulfate by Tenny and Stumm (12), (1964), and by Eberhardt and Nesbitt (33), (1967); ferric chloride, aluminum sulfate and sodium aluminate by Barth and Ettinger (34), (1967). Dosage efficiency has varied with species of salts used, points of injection, % removal and residual phosphorus attained, resultant pH, and with precision in proportional dosing. Effective mol doses--ratio of mols of chemical applied to mols of phosphorus removed--include the following: 7/1, Fe/P, by Sawyer (17) using ferric chloride for 91% removal of P from raw wastewater, reduction from a level of 2.2 mg/l down to 0.2 mg/l, no resultant pH reported; 3.7/1, Al/P, by Mahlorta, et.al. (23),

using aluminum sulfate in secondary effluent, for 94% removal, reduction from 7.6 mg/1 P to 0.5 mg/1, at pH 6.0; 3/1, Fe/P, by Wuhrman (24), using ferric chloride in aeration liquor, for 88% removal, reduction from 6 mg/1 P to 0.5-1.0 mg/1, at pH 6.8-7.5; 1.9/1, Al/P, by Eberhardt and Nesbitt (33) using aluminum sulfate in aeration liquor, for 93% removal, from 13.8 mg/1 P to 1.0 mg/1, at pH 5.5; and 1/1, Al/P, by Barth and Ettinger (34), using sodium aluminate in aeration liquor, for 95% removal, reduction from 12 mg/1 P to 0.6 mg/1, at pH 7.2-7.5. The effective mol ratio of 1/1, Al/P, observed by Barth and Ettinger was attributable to rigid control of proportional dosing, to resultant pH being near optimum, and to upwards of 40% of the removal being biological precipitation of phosphorus.

Three different reaction mechanisms have been considered as operative in precipitation of phosphorus with iron and aluminum: chemical precipitation by ion combination at pH levels of minimum solubility, Tenny and Stumm (12), (1965); physical adsorption with pH dependence, Lea, et.al., (30) (1954); and complexation of hydrolytic products, also pH dependent, Singley and Black (35), (1967).

The available information cited above, the considered operative mechanisms of reactions, plus pre-demonstration bench-scale studies pointed to best points of injection, process control, and mol doses for most efficient use of iron and aluminum at the Texas City plant. Under treatment scheme number one, for removal of phosphorus from recycle digester liquor the effectiveness and feasibility of the use of ferric and aluminum chlorides were to be compared with the use of lime. Under treatment scheme number two, for supplementing uptake of phosphorus in primary and aeration processes, four chemicals were to be tested: ferric

chloride, ferrous chloride, ferrous sulfate and aluminum chloride. Injection was to be into raw influent for limited removal of phosphorus in primary units, with carry-over of soluble and precipitating iron and aluminum for continuing precipitation in aeration units. Then, injection was to be into the aeration influent for augmentation of uptake of phosphorus by activated sludge.

THE TREATMENT PLANT, OPERATIONAL FEATURES AND LIMITATIONS

The treatment plant, Texas City No. 2, is a conventional activated sludge plant of 0.7 MGD (2650 cu m/day) rated capacity. The plant layout and flow schematic, including auxiliary facilities for chemical treatment, are shown in Figure 1.

The wastewater from a resident population of about 5000, plus a 325 bed hospital, reaches the plant through 5000' of 24", then 1000' of 36" concrete sewer (1520 meters of 61 cm, then 305 meters of 91.3 cm). These sewers were utilized as surge reservoirs for increased uniformity of flow.

The wet-dry lift station includes two comminutors; a 500 GPM (1.898 cu m/min) and a 700 GPM (2.66 cu m/min) pump for through-plant flow; and a 2500 GPM pump (9.5 cu m/min) for by-pass during heavy infiltration. Automatic sequential pumping control is provided, but manual control prevailed for these demonstrations.

The aerated degritter was effective for coarse grit, but not for fine silt of heavy infiltration. Troublesome quantities of silt and sludge accumulated in primary and secondary clarifiers which entailed periodic heavy aeration of clarifier bottoms and hoppers to facilitate transferal to the digester.

Overflow rate of the primary clarifiers is 1040 gal/sq ft/day (42.4 cu m/sq m/day). Overflow weir length is only 10 ft. (3.0 m) per clarifier. Flow-through patterns were not quantitatively evaluated but were evidently poor at mean to higher flow. Baffle improvisation effected improvement. One of the primaries was utilized as a waste sludge thickener for considerable periods, leaving only one for primary clarification.

The secondary clarifiers, rated at 670 gal/sq ft/day, (27.3 cu m/sq m/day) have 25 ft (7.5m) overflow weir length per unit. Baffle improvisation also gave improved flow-through patterns, particularly at high rates, permitting through-plant flow as high as 1.3 MGD (493.0 cu m/day).

The two aeration tanks, 60' x 20' x 12' (18 m x 6 m x 36 m) afforded 216,000 gallons aeration volume (819 cu m), rated at 6 hours aeration based on .7 MGD plant flow (2650 cu m/day). The aeration flow-through pattern was much closer to complete mix than to plug flow, due to the low length to width ratio, to high return sludge rate (50-100%) and to turbulent mix.

A single speed, plus a two-speed blower afforded five-step air application rates. The highest rate, 1600 cfm, (45.3 cu m/min) was marginally adequate in hot weather, during periods of highest BOD and solids loading.

The digester is 42' in diameter and 21 ' in depth to the top of the conical bottom (12.6 x 6.3 m) equivalent to about 220,000 gallons volume (834 cu m). On basis of a 6000 sewered population, this allows approximately 4.7 cu ft (133 l) per capita. It is estimated that a 15 year accumulation of sand and silt has reduced the digester volume by at least 30%.

Digestion capacity was adequate when augmentative iron was used in primary and secondary treatment but barely 50% adequate when aluminum was used. The eight separable 42' x 44' (12.6 m x 13.2 m) sludge drain beds afforded adequate capacity during the 2-year demonstration, but marginally so through prolonged rainy periods, and immediately following the 2-month production of high alumina sludge. Drain bed liquors were recycled to the plant influent. Digested sludge was utilized for land fill and soil conditioning of plant grounds and adjoining areas.

AUXILIARY FACILITIES FOR CHEMICAL TREATMENT

Digester liquor was drawn by siphon and pumps through a strainer, from 4-6 feet depth, at 10-30 GPM. A 1 to 3 minute quick mix with lime was effected through the slurrier box of a dry lime feeder. Precipitation and solids conditioning were completed in a 1000-gallon (3.79 cu m) tank by gentle but complete mix aeration. Dewatering of the conditioned slurry was by subsidence and overflow drainage in a compartmentalized 42' x 44' section of the sludge drain bed. When aluminum or iron was used, injection was into the digester liquor line to the flocculation solids-contact tank. Dewatering was also on the sand drain bed.

Liquid chemicals were stored in neoprene-lined and glass-lined steel tanks, 3500 gallons (13.27 cu m) total capacity. Feeding of liquid chemicals was by means of chemical metering pumps. Transmission of chemical feed to plant injection points was through small plastic pipe and hose.

SAMPLING AND ANALYTICAL PROCEDURES

For monitoring of around-the-clock parameter variations, process samples (Figure 1, Flow Schematic and Process Units) were collected as needed and appropriate tests made at the time, or samples were refrigerated for delayed analyses. Sludge settleability, and phosphorus and solids content were measured three times daily. Temperature and pH readings were made once to thrice daily. Dissolved oxygen readings were made on the aeration effluent at least bihourly, by means of DO probes in situ. Survey DO readings were made at other process points as needed.

For monitoring daily variations in COD, solids, phosphorus, nitrogenous components, chlorides, alkalinity, calcium, magnesium, iron and aluminum, bihourly samples were collected and refrigerated, then composited proportional to flow, at the end of each 24-hours.

The COD test was routine for measuring organic loadings and reductions. Sufficient BOD_5 tests were made to show approximately a 10:6 ratio of COD:BOD_5 on raw influent and primary effluent samples, and a 10:2 ratio on final effluent samples.

Calcium, magnesium and iron were measured by atomic absorption. The spectrophotometric method, published by Davenport (36) in 1949 was used for simultaneous determinations of iron and aluminum. For total phosphorus — inorganic plus organic — samples were digested to fumes of sulfuric acid and to a colorless digestate, from a 1:4:5 by volume solution of sulfuric acid, nitric acid and water. All other analytical procedures were in accordance with "Standard Methods for the Examination of Water and Sewage" (37).

DEMONSTRATION PROCEDURES AND RESULTS

REMOVAL BY ACTIVATED SLUDGE
NO ADDED CATIONS

Plant-scale studies of operation at the Texas City, Plant #2, with no cations added to primary or aeration processes, were initiated in June, 1968. At that time, and until January, 1969, there was evidence of biological phosphorus enrichment of aeration solids. After that time, there was none. Ranges of levels of removal of phosphorus for representative demonstrations periods, and of concurrent levels of other parameters, are listed in Tables I-III. Data for some of the parameters are represented graphically in Figures 2 to 8.

Basically, operation control was in line with the regime that had been empirically developed by the plant operators, for maximum day-to-day removal of BOD and suspended solids: first, accept flow up to maximum solids retention capacity of secondary clarifiers; second, clean, skim, and withdraw solids from primary and secondary clarifiers for cleanest, "freshest" conditions; third, return and waste sludge, apply air and waste solids for best physical appearance and settleability of aeration solids; and fourth, withdraw digester sludge to drain beds as necessary to prevent excessive "black" solids being recycled to the system with digestor liquor. Operation records show that by this regime an effluent goal of less than 20 mg/l BOD and suspended solids was maintained when aeration solids (MLS) were within the range 1500-2000 mg/l, and dissolved oxygen (DO) in the aeration tank effluents was as much as 1 mg/l.

In the demonstration periods (Tables I and II) operational control included the following supplementary modifications and intensifications over the regime of previous operation.

a. Greater uniformity of through-plant flow was maintained by utilizing the 6000 ft (1830 m) of influent trunk sewer as a surge line during the daily peak flow periods.

b. A larger proportion of flow was accepted through the plant, except experimentally, and somewhat of necessity, August 1 - September 3, 1968 (Table II).

c. Digester liquor was not recycled through primary and aeration processes unless it contained less than about 30 mg/l of phosphorus.

d. Wasting of activated sludge was directly to the digester instead of through the primary clarifiers. After December, 1969, one of the primaries was used as a thickener for waste aeration solids (MLS), and only one primary was used as a clarifier for raw influent.

e. Hourly to bi-hourly readings of DO in the aeration effluents were made for more rigid control of air application.

f. A more intensive monitoring schedule was maintained for all control and index parameters.

Removal, when there was Phosphorus Enrichment of Aeration Solids

Pre-demonstration observations, July 1967 to May, 1968, revealed that the phosphorus content of aeration solids often was as high as 4 to 5%, dry weight basis. Thus, a prime requirement of effective removal of phosphorus was being met. Assay of 24-hour sample composites indicated occasional through-plant removal of 30-40%, but on the average only 10-15%. The low removal was attributed to the operational practice of recycle of digester liquor to the raw influent and wasting of aeration solids through the primary clarifiers, thus, returning soluble phosphorus to the system.

A first opportunity was afforded, June 2-9, 1968, to observe phos-

phorus removal without recycle of digester liquor and with aeration solids wasted directly to digester. On May 31, digested sludge was withdrawn to about 6 feet below overflow level in the digester. By June 2, sand bed draining had subsided, and it was not until June 9, that the digester was refilled to overflow level. Wasting of aeration solids to primary clarifiers was interrupted June 1. Phosphorus removal was at 59% and 51% on June 3-4, and ranged down to 21% and back to 57%, June 4-9 (Table II, June 2-9, and Figure 2, June 3-5). Composite samples on alternate days, June 11-17, indicated removal of 24 to 55%, with recycle of digester liquor but with no wasting of solids to primaries. Phosphorus in aeration solids held at near 5%.

Multiple periods of heavy rainfall and excessive sewer infiltration, plus interrupting sewer cave-ins and equipment failures, afforded, opportunely, wide variations in hydraulic, COD, suspended solids and phosphorus loadings, and required improvisations of operation. Results of operation under these conditions did not delineate, but pointed to the significant limitations to adaptation of this and similar plants for effective removal of phosphorus, without added cations; that is, the normal and abnormal variations themselves.

Normal dry weather flow; no primaries; 70-80% loading – From June 24 to July 14, there was a 21-day interruption of operation of secondary clarifiers. Aeration solids dropped to less than 400 mg/l, of less than 1% phosphorus content. Then, on July 16, 2 days after restoration of secondary clarifiers, the primaries went out of service. Replacement and repairs of equipment were not completed until November 28, 1968. Thus, of necessity, but opportunely, operation was without primary clarifiers for 134 days.

By August 1, aeration solids had built to above 1500 mg/1, of 2% phosphorus content. Normal dry weather flow prevailed for 34 days (Table I, Columns 1-3; Table II, August 1 - September 3). Weather was hot, and aeration capacity was deficient for maximum loadings. Therefore, through-plant daily flow and loadings were limited to levels that permitted an experimentally desired DO near 1 mg/1. Through-plant flow was held close to 0.4 MGD (1515 cu m/day) 18-22 hours but dropped to about 0.3 MGD during mid-A.M. (Figure 3a). Minimum COD, suspended solids and phosphorus loadings were concurrent with minimum flow, and maximum with peak total flow of early afternoon (Figures 3 and 3a). Sludge return rate was 80-90% of through-plant flow. Aeration solids (MLS) were held at 1500-2000 mg/1, and DO in aeration effluent at 0.5-1.5 mg/1, average, 0.8 mg/1. COD to solids loadings, lbs/COD/day/lbs of MLS, were in the range of .22-.42, average, .32. COD to phosphorus loadings, lbs COD/lbs P were 21/1 to 50/1, average, 28/1. Thus, for 34 days, there was an approach to a steady state of parameter variations, of lowest possible amplitudes.

Daily levels of parameters are listed in Table I. Ranges and averages for the 34-day period are compared with those for other demonstration periods in Tables II and III. Daily to 8-hour variations are represented graphically in Figures 3 and 3a. The 52% removal for 3 days (August 14-16, Tables I and II and Figure 3a), and the average of 43% for 15 days (August 10-24, Table I), indicated that control at about 50% removal might be attained. But the failure to do so, even when levels of parameters were of the same order of reproducibility, was evidence that it would be difficult.

Wet weather flow; no primaries; maximum possible loadings – Results of the 34-day period, August 1 to September 3, indicated that higher COD loadings and a lower DO level might be tolerated, with resultant higher removal of phosphorus. It was so planned for September and October. But recurrent heavy rainfall and infiltration precluded desired control of loadings, DO, aeration solids and the phosphorus content of aeration solids. For example, note the variations September 3-7, with best efforts to hold daily loading at 80% of average (Table I, and Figure 3). Heavy rainfall September 3-4, raised total flow to 1.8 MGD. Through-plant flow was held at .66 MGD September 4, because of evident flushing of accumulation of solids, COD and phosphorus from sewers and lift stations, but was raised to 1 MGD September 5-6, because of evident dilution. Control of DO at the 1 mg/l level was lost. Aeration solids (MLS) dropped, due to dilution and to some loss to effluent. Phosphorus content of solids dropped to 1.5%, attributed to loss of biological phosphorus enrichment and to dilution by inorganic solids. Phosphorus removal dropped to as low as 6 and 7%. See also similar variations September 15-19, following heavy rainfall September 13-14 (Figure 3).

After September 7, 1968, for the duration of the Demonstration Project, no further attempt was made for experimental limitation of raw influent loadings of COD, solids or phosphorus. Total flow was accepted through the plant except when infiltration raised flow to above the hydraulic capacity for retention and removal of plant solids, or when, on a few occasions, there was lift pump failure. From September 4 to October 1, in spite of uncontrolled variations in raw influent loadings, the desired increases of COD/MLS loadings and reduced aeration DO levels were experienced, but on the average with no correlative increase in

phosphorus removal. Compare, September 4 - October 1, with August 1 - September 3, Table II; also Figure 3. Moderate infiltration from lighter rains of September 6, 13, and 20 brought considerable slugs, then dilution of COD, solids, and phosphorus, which affected control of DO and reflected reductions in phosphorus removal. Heavier infiltration from heavy rain of September 4 and 14-17 produced wider variations, and phosphorus content of solids dropped to below 2% (Figure 3). A minimum 3-day average of only 19% removal was registered September 15-17 (Table II). Phosphorus content of aeration solids had built to 3.5% by September 25 and to 4.3% by October 1. Phosphorus removal was 69% September 25, 67% October 1, averaged 59% September 24-26, and averaged 51% for the eight-day period September 24 to October 1 (Figures 3 and 4, and Table II).

October 2-4, there was a 50-hour interruption of operation due to a sewer cave-in. Aeration solids were held under gentle aeration and phosphorus content at 4%. Rainfall October 5-6, brought increased flow and loadings. There was some release of phosphorus from aeration solids October 6, reducing net removal to 9% (Figure 5). Total flow and loadings were accepted on October 7 and 8. There was some recovery of phosphorus in aeration solids. More rain came October 8-9, very heavy on October 9, raising sewer infiltration to a very high level October 10, bringing much inorganic solids, flushing out accumulation of organic solids from lift stations and sewers, and diluting and "washing out" soluble phosphorus. There was essentially no loss of aeration solids to the effluent through October 10. Aeration DO was held close to 1 mg/l October 5-9, but went out of control October 10. Phosphorus removal, October 7, 8, and 9 was at 78, 67 and 65%

respectively. Materials balance measurements became tenuous with the "wash out" conditions of October 10, but the indicated phosphorus removal was only 20% (Figure 5).

The flood conditions of October 10-11, entailed complete shutdown of the plant lift station pumping equipment, October 12-21. With auxiliary pumps, an unmeasured through-plant flow of 0.2-0.4 MGD (760-1520 cu m/day) was maintained October 13-20. Aeration solids were held at 2100 mg/1 and DO at .9 mg/1. Phosphorus content of solids held at 2.5 to 3.0%. Daily phosphorus removal averaged 43%.

Average flow; no primaries; near maximum loadings— From October 22 to November 29, with much less rainfall, it was possible to accept, through the plant, 93% of the total flow. Average daily flow was close to the design capacity of 0.7 MGD, and close to the "normal" average, (Table II, October 22 - November 26, 1968). Daily COD/MLS loadings held close to 0.4, an experientially indicated effective level. Aeration effluent DO was varied from 0.4 to 2.0 mg/1. Per cent phosphorus in aeration solids held close to 3.0% for the first 15 days, fell to 1.7% during the next 15 days, then rose to 3.0% the last 6 days of the 36-day period. The low phosphorus removal experienced--29% average for the period, 14% for a low 3-day average, and only 46% for the highest 3-day average (Figure 7 and Table II)--was attributed to accumulation of raw grease-laden solids in aeration solids and in the secondary clarifiers. There was increasing evidence of the raw "debris" in the aeration and return solids early in the period. Aeration DO level was raised but with no measurable improvement. Then, it was noted that a heavy accumulation of silt- and grease-laden anaerobic sludge in the secondary

clarifiers was releasing soluble phosphorus to the effluent and to return sludge. The deposition was removed by brief periods of heavy auxiliary aeration of the clarifier hoppers and bottoms, with some loss of solids to the effluent. The phosphorus content of return and aeration solids had dropped to a low of 1.7%, and the 3-day low of only 14% removal of phosphorus was registered (Table II, November 18-20). Further accumulation of solids in the clarifier was prevented by daily aeration of the clarifier bottoms and hoppers, during brief interruptions of plant flow. Phosphorus in aeration solids rapidly recovered to 2.8% and the 3-day high of 46% removal was registered November 24-26.

Primaries restored; wet-wet weather; 70-90% loadings — The primary clarifiers were restored to service November 27-28. Operation with no cations added to primary or aeration processes was continued through January 19, 1969. Moderate to heavy rains recurred weekly to bi-weekly. Total flow averaged 1.06 MGD. Through-plant flow was .86 MGD, 81% of total. Phosphorus content of aeration solids dropped to below 2% with each succeeding increase of infiltration flow. COD/MLS loadings averaged about .3/1. Aeration effluent DO was held in the range of 1 to 2.5 mg/1, at an average of 1.3-1.4 mg/1 for maintenance of settleability of aeration solids, and of low effluent COD. The maximum, minimum and mean 3-day average removals of phosphorus were 37, 0, and 15% respectively (Table II, November 29-January 19). These low levels of removal were attributed to "wash out" of phosphorus enrichment of solids at times of high infiltration flow; to some loss of solids to effluent at peak through-plant flow; and to endogenous destruction of solids by extended aeration of the sludge of considerable age, 4 to 6 days.

Removal when there was no Phosphorus Enrichment of Solids

Operation with no cations added to primary or aeration processes was interrupted January 20, 1969, for a demonstration of the use of iron, but was reinstituted for 30 days June 15, and later for three other periods of 9-19 days (Table III). Dry, to dry-dry weather prevailed. Total flow was accepted through the plant except for a few days July 1-14, when failure of one of the through-plant lift pumps limited flow to 88% of total. Only one of the primaries was used as a clarifier for raw influent. The other was used as a thickener of waste sludge. The use of the influent sewer as a surge line effectively levelled diurnal peak and minimum flow, but not so effectively the COD, solids and phosphorus loading rates (See typical diurnal flow and loading patterns Figure 8; also Figures 3a, 4, 14 and 15).

Digester supernatant liquor was recycled to the raw influent, in that soluble phosphorus never rose above 30 mg/l after the periods of iron treatment in primary and aeration processes January 20 - June 13, and aluminum treatment August 21 - October 15; also, in that much of the digester liquor was unavoidably recycled as drainbed liquor from frequent and heavy digester draw-down during the dry summer month. Recycled supernatant contained excessive solids for a few days October 18-November 14, therefore higher levels of suspended phosphates--50-100 mg/l P, as alumina-phosphate--but amounting to less than 1 mg/l additional phosphorus in the raw influent.

Average daily COD to aeration solids loadings, COD/MLS, for the various periods (Table III) from .39/1 to .56/1, were appreciably higher than for periods when there was evidence of phosphorus enrichment of solids (Compare data of Tables II and III; see also Table I). Air

application was at maximum capacity rate for diurnal peak loading period, and at sufficient rate at low period to maintain, on the average, about 1 mg/l aeration effluent DO. Sludge settleability was poor, as indicated by the 30-minute test (Compare SVI data of Tables I-III). And yet, solids retention and removal through secondary clarifiers were effective, except at times of extended denitrification, eg, October 18-29, with loss of more than 30 mg/l solids during the period (See effluent suspended solids, Table II). Effluent COD averaged slightly below 40 mg/l, except October 24 - November 14, when there was excessive loss of solids to effluent and recycle of abnormally high COD digester liquor.

At no time was there evidence of phosphorus enrichment of aeration solids, nor of effective uptake of phosphorus. Note: The 2 to 4% phosphorus content of aeration solids June 15-30, and October 18-29, was due to residual ferri-phosphorus and alumina-phosphorus content of the solids from the immediately preceding periods of iron and aluminum treatment, respectively, (Table II). Daily phosphorus removal never exceeded 20%, and averaged only 10 to 15%.

Presumably the failure to attain higher phosphorus enrichment of aeration solids, and thereby higher removal of phosphorus was due to the absence or deficiency of micro flora or fauna capable of biological phosphorus enrichment.

Even if such species were present, the combination of low flow-heavy load, the diurnal variations in loadings, the near complete mix of aeration, the long sludge age and endogenous degradation of solids imposed nutrient balance conditions unfavorable to maintaining adequate biological phosphorus enrichment (7, 8, 9).

REMOVAL AND DISPOSAL OF
PHOSPHORUS FROM DIGESTER LIQUOR

To minimize recycle of phosphorus to plant treatment processes, phosphorus was precipitated from digester liquor; the solids drained on sludge drain beds; and the filtrate, containing less than 10 mg/l P, returned to the plant influent. Hydrated lime was used through most of plant operation when no cations were being added to primary or aeration processes, July 1968 to January 1969. The effectiveness of Fe(III) and Al(III) were studied for brief periods.

Precipitation with Lime

The flow and chemical injection, reaction and disposal processes are indicated schematically in Figure 1. Liquor was drawn from a 3-4 ft depth in the digester, through a cylindrical strainer, 4" x 10", with 5/8" holes on 1" centers (10.4 x 26 cm with 1.62 cm holes on 2.6 cm centers). Flow rates were varied from 10 to 30 gpm (38-114 l/m) with most operation at 20-24 gpm. Full flow was taken through the slurrier box of a dry lime feeder, for a quick mix-slurry time of 1 to 2 minutes; then, by gravity to the top and over the edge of the 1200 gal (4.6 cu m) neoprene-lined reactor tank. An underflow baffle extended to 1' of the bottom on the outflow side of the reactor. Air agitation was maintained, sufficient to keep the mass of solids suspended, but stratified into a sludge blanket toward and into the outflow compartment. Reactor effluent was from near the top of the reactor, by gravity, 200' (62 m) to the edge and over the side of a 42 ft by 44 ft (13 x 13.6 m) section of the plant sludge drain bed, for solids subsidence and draining, and for overflow of supernatant to another section of the drain bed. All transmission lines were 1½-in and 2-inch (3.9 and 5.2 cm) plastic (PVC) pipes, except

the line from the slurrier to the reactor tank. This was replaced by a 3½" x 3½" (9.1 x 9.1 cm) wooden trough to facilitate removal of depositions of magnesium ammonium phosphate.

Intermittent operation of the process, 6-24 hours, 2 to 3 times per week was sufficient to prevent overflow of untreated liquor from the digester to the plant influent.

Lime dosage was at various levels, to determine the minimum required to reduce the phosphorus content to below about 10 mg/l; with production of least quantities of solids of best drainability; also with least solids deposition on slurry transmission surfaces.

Operational parameters and results for representative days of operation are shown in Table IV. The periods are listed 1 to 11 in ascending order of pH levels of reactor effluent, which, experientially, was the best index for control of lime dosage.

The soluble phosphorus content of the liquor was regularly reduced to about 10 mg/l, when the pH of the reactor effluent was maintained as high as 8.5; optimally, not higher than about pH 9.0.

For the experiential phosphorus levels in the digester liquor, 80 to 250 mg/l, a major proportion of the lime dosage was consumed by carbon dioxide and ammonium bicarbonate; then, at increasing doses of lime, by precipitation of calcium carbonate. Since acidity and alkalinity in the liquor did not increase greatly with increased phosphorus content, efficiency in lime usage increased with increased phosphorus content, i.e., ratios of lime to phosphorus were lower (See AMR and EMR values, Table IV).

At phosphorus levels above about 200 mg/l there was rapid deposition

of magnesium ammonium phosphate ($Mg \cdot NH_4 \cdot PO_4 \cdot 6H_2O$, as assayed) on the walls, and on the outflow orifice and line of the slurrier, but such deposition did not extend to the surfaces of the reactor tank or its outflow line. The deposition was so severe in the slurrier outfall line that operation had to be interrupted every 4-6 hours for cleaning. But, by replacing the outfall pipe with a wooden trough the cleaning was readily accomplished without interruption of operation.

Settling and draining of the solids of the reactor effluent were rapid in the 42' x 44' section of sludge drain bed. It was not until after several intermittent days of operation that a 10-12 hour operation period would fili the bed with liquor to the 14-inch overflow level. Overflow and drain-bed liquors were clear, only slightly colored, and of slightly lower soluble phosphorus content than the reactor effluent (Table IV).

Removal of solids from the digester liquor was complete. Removal of COD was 60 to 80%, with no discernible correlation of phosphorus and COD removals. Removal of ammonia was measurable only at operation pH levels above about 9.0. There was evidence of escape of ammonia from the reactor and drain bed surface during and immediately following operation at the higher pH levels.

Drain-down of the bed was complete within 12 to 18 hours after interruption of operation. And cracking of the sludge cake surface would develop within 48 hours. Cracks would widen and deepen rapidly when interruption of operation was extended as long as 6-8 days. Also a heavy algal growth would develop over the surface and down into cracks.

At the end of drain down, with incipient cracking , the sludge would be about 30% solids, dry weight basis. By the time cracks developed to

full depth, solids content was about 60%. Figure 1a is a photograph of the bed when moisture content was in a 20-30% range. With long standing, under dry weather conditions, the solids dried to a friable cake of about 15% moisture content. Removal and disposal was demonstrated at the 40% and 15% moisture content stages, by the spade-fork-truck process, for fill and spreading on plant grounds. Representative analyses of the solids, dry weight basis, was .15% nitrogen and 4.3% available phosphorus. Spreading on plant grounds gave evidence of plant growth stimulation. Best utilization of the solids would be on acid soils deficient in phosphorus.

Precipitation with Iron and Aluminum

Opportunity was not afforded for extended plant-scale demonstration of the use of iron or aluminum for precipitation of phosphorus from digester liquor. The studies of the use of lime extended into January, 1969. By that time, the low phosphorus content of waste sludge, and considerable pumping of thin sludge to the digester, had reduced phosphorus content of digester liquor to less than 100 mg/l. Then, with injection of iron into raw influent or primary effluent, initiated January 21, the phosphorus content rapidly dropped to below 30 mg/l. At this level, further reduction for recycle was not deemed justifiable, and results of demonstration studies were not representative for treatment of liquors of higher phosphorus content.

Laboratory grade ferric chloride ($FeCl_3 \cdot 6H_2O$) and an ore processing by-product ferric chloride (10-15% available Fe(III)) were used in bench-scale studies. The latter was used in plant-scale demonstrations. A waste by-product aluminum chloride, from polystyrene manufacture (5%

available aluminum) was used in bench-scale studies and in two 6 to 8-hour plant scale demonstrations.

In bench-scale and plant-scale tests on liquors containing 30-60 mg/l phosphorus, doses of Al(III) or Fe(III) at mol ratios of about 1.5/1 effected 95% removal. Flocculation and sedimentation were rapid, but compaction of the alumina-phosphate floc was poor. Buchner funnel filtration of total flocculated volumes was poor, particularly of the alumina-phosphate. Filtration of supernatant volumes was rapid, which pointed to the most feasible scheme for plant-scale dewatering on sand drain beds.

In plant-scale tests, the ferric chloride, or aluminum chloride, was injected into a 20-25 gpm (76-95 lpm) stream of digester liquor through 30 feet of 1½"PVC pipe, with out-flow over the top of the 1200-gallon (45.5 cu m) reactor tank (Figure 1, refer also to lime treatment, above). Gentle air agitation was maintained in the influent compartment of the tank (about 3/4 of the volume), just sufficient to keep the mass of the floc moving under the bottom of the baffle into and through the outflow compartment. The reactor effluent was transmitted through 2½-inch PVC pipe to a 42 x 44 ft section of the plant sludge drain bed. Subsidence was rapid in the influent areas of the drain bed, to a 4-5% slurry of ferri-phosphate, or to a 2-3% slurry of alumina-phosphate. The liquor drained with decreasing rapidity through the accumulating settled sludge, but the supernatant drained very rapidly at the creeping edge of the sludge. It was indicated, though not adequately demonstrated, that by using a second compartment for draining of the supernatant, as much as 12-15 inches of a 5% sludge of ferri-phosphate or a 3% sludge of alumina-phosphate could be accumulated

in the first compartment of a two-compartment operation--subsidence, and overflow withdrawal and draining of supernatant liquor. The second compartment would need to be no more than ½ the size of the first.

Bench-scale tests were made on digester liquor fortified to 350 mg/l of phosphorus by addition of orthophosphate. Reduction to less than 10 mg/l was effected by mol doses of 1.2/1-1-4/1, Fe/P or Al/P plus about a 1/1 mol dose of lime to hold pH at 4.5-5.0 for iron and 5.0-5.5 for aluminum. Thus, it was indicated that the use of iron or aluminum for precipitation of phosphate from high phosphorus liquor would also entail the use of lime, or other suitable alkali.

UTILIZATION OF IRON IN PRIMARY AND AERATION PROCESSES

The initial project concept, and the key objective of treatment scheme number two, was to utilize iron, lime, or aluminum for augmenting phosphorus uptake by aeration solids. But it became evident that control of biological uptake of more than 15% of the phosphorus load would be difficult if not impossible. Therefore, for 80-90% removal, the augmentation and the total removal would be approximately equivalent. Demonstration objectives were then set for determining the preferable chemical, the best points of application and the best overall operational control under variable flow and loadings for removal and disposal of 80-90% of the plant phosphorus load.

For the use of iron this meant: first, the use of ferric or ferrous iron; second, applied to primary effluent or to the raw influent; third, at single or two-level diurnal dosage rates; and fourth, at the required

daily mol dosages Fe/P, for uptake of 80-90% of the phosphorus by the plant solids and for holding the phosphorus with the solids through digestion and drain bed drying.

Ferric and ferrous chloride were procured from Gulf Chemical and Metallurgical Company, Texas City, Texas. These were by-product solutions from ore processing, of satisfactory purity, ontaining 8 to 12% available iron and very little excess acid. High purity ferrous sulfate pickle liquor, 5 to 8% available iron, was supplied by the Chemlime Corporation, La Porte, Texas. Delivery prices in the Texas City - Houston area, during the project, were $0.09-0.12 per pound of available iron.

Operation control of overall plant processes was close to that for operation with no cations added to primary and aeration processes. It was possible to accept a larger proportion of excess infiltration flow due to the heavier, better settling high iron sludge.

Experimentally and inadvertently, dissolved oxygen (DO) in the aeration effluents ranged from 0.3 to 3.0 mg/l with indications that 1 mg/l was adequate, and near optimum. A slightly lower level gave better control of denitrification, for minimum gas-floating of solids in the final clarifiers.

Experimentally, aeration solids (MLS) were varied from 1500 mg/l to 4000 mg/l, with indications that overall treatment effectiveness was favored at greater than 3000 mg/l, when aeration capacity was sufficient to keep DO in aeration effluent as high as 0.5 mg/l.

Return sludge rate was at about 0.5 MGD (1900 cu m/day), equivalent to 90-100% of dry weather plant flow. Except for May 18-29 and December 20-31, 1969, and January 1, 1970, sludge wasting was to primary clarifiers, with satisfactory thickening, with measurable but not highly significant uptake of phosphorus and reduction of raw solids and COD. During May 18-29, sludge was

wasted directly to drying beds for testing of drainability and open bed digestion feasibility. December 20-31, 1969, and January 1, 1970, sludge was wasted to one of the primaries operated solely as a sludge thickener.

Digester liquor was returned to the plant influent. After only about 5 weeks of iron application to primary and aeration processes, the digester liquor contained less than 25 mg/1 of phosphorus, entailing no significant recycling of phosphorus.

In a first period of studies of utilization of iron, 145 days, January 20 through June 13, 1969, there was continuing frequent and heavy rainfall, with resultant heavy infiltration. The estimated average flow to the plant for the 145 days was 1 MGD (3790 cu m/day), of which an average of .86 MGD (3260 cu m/day) was accepted through the plant. Daily concentration of phosphorus ranged from 2 to 10 mg/1, at a weighted average of 6.3 mg/1 for the period. (Tables VI and VII, compare total and through plant flow; also, the raw influent phosphorus).

A second period, 54 days, November 15, 1969, through January 7, 1970, included 22 days of low dry weather flow, averaging .53 MGD (2000 cu m/day) of 13.5 mg/1 phosphorus. Thus, opportunity was afforded in the two periods to test the mol dosage effectiveness over a wide range of influent phosphorus concentration. Results indicated that a given mol dosage Fe/P was equally effective for various influent phosphorus levels experienced at most treatment plants.

Rigid proportional chemical dosing was not attempted, only single level and two-level diurnal rates. A mol dosage, Fe/P, was selected for a period of days. Then, based on pre-knowledge of daily phosphorus loads, e.g. approximately 45 lbs on Saturdays and 65 lbs on Mondays, etc., the required volume of chemical solution was estimated for the respective days. Then, for a given day, the required volume was fed either at a single level uniform rate,

around-the-clock; or at a two-level rate, i.e. at a low rate approximately proportional to the expected low phosphorus loading for 4 to 6 hours during mid-A.M., and at a higher rate approximately proportional to the average phosphorus loading during the remaining 18 to 20 hours (See flow and phosphorus level patterns, Figures 9 - 12). Initially, and for 175 of the 199 days of iron application, dosage rate was single level. The results of a six-day period of two-level rate indicated significantly greater efficiency over single level dosing of ferrous iron to the primary effluent. A two-level rate for a 1.32 mol dose, Fe/P, effected 87% removal of phosphorus, as compared to 79.70% removal by a 1.38 mol dose, applied at single rate, under comparable conditions of operation (Table VIII, Fe(II) to primary effluent, April 25-30 and 19-24, respectively). No comparison was made for feeding of ferric iron to primary effluent, nor to the raw influent. A greater efficiency would be expected for two-level over single-level dosing of ferric iron.

The results of 17 days of two-level dosing of ferrous iron to the raw influent indicated only slightly better efficiency of iron utilization over single level dosing (Table V; Table VIII, Fe(II) to raw influent; also Figures 10-12).

Ferric and Ferrous Iron to Primary Effluent

A moderately quick mix of dosing chemical was effected by injection into the primary effluent just as it merged with the turbulent inflow of return sludge (Figure 1, RS and PE), and mixing was near complete before division of the combined stream to the two aeration units. This was adequate for ferrous iron in that mixing was complete before total oxidation and hydrolysis of the iron; but was marginally so for ferric iron, due to considerable hydrolysis before homogenity was attained. It is suggested that this is a partial explanation for the observed less efficient utilization of iron from ferric than from ferrous.

Ferric iron was dosed to the primary effluent for 18 days, during variable wet weather flow (Columns 1,2 & 5, Table VI), and for 20 days during prevailing dry weather flow (Columns 3, 4 and 6, Table VI; also Fe(II) to Primary, Table VIII). All dosing of Fe(III) to the primary effluent was, diurnally, at a single-level rate. Dosing of Fe(II) to the primary effluent was for a total of 34 days, during variable wet weather, at single level diurnal rates, except for six days (Columns 7-11, Table VI; also, Fe(II) to Raw Influent, Table VIII).

Attempts to carry out a series of experimentally desired incremental mol doses were frustrated by extreme variations in daily flow and phosphorus loadings. But, "after the record," it was possible to select 3-day to 11-day periods in which the daily doses, and the levels of other parameters for a given period, were sufficiently close to the averages of the period, for the average iron dose to be meaningful; i.e. with respect to phosphorus removal effectiveness of such an average mol dose, Fe/P. The averages of doses, raw and effluent phosphorus levels, phosphorus removal and of phosphorus insolubilization are summarized in Table VIII for six such periods of dosing Fe(III), and five such periods of dosing Fe(II) to the primary effluent. These data are compared with data for other parameters in Table VI. Control and index parameters were not wholly comparable from period to period, but sufficiently so to indicate better removal efficiency by Fe(II) than by Fe(III). Mol doses (AMR, applied mol ratios, Fe/P) of Fe(II) at about 1.3/1 effected about 80% removal of phosphorus. Mol doses of about 1.6/1 were required for equivalent removal by Fe(III).

Operation conditions particularly were non-comparable for the period November 15-22, 1969 (Column 4, Table VI; also line 4, Table VIII). This was a start-up period. It had been noted that upon initiation of iron treat-

ment, insolubilization proportional to dosage was immediate, but adequate flocculation was not attained until about the third day. Poor flocculation persisted through the period, November 15-22, with resultant effluent solids at an average of 35 mg/1, and phosphorus removal of only 58%, at the average applied mol dose of 1.35/1. It was not until the sequential period, November 23-30, at a mol dose of 1.16/1, did flocculation improve, effluent solids decrease and phosphorus removal increase. This was attributed to the continuing build up of phosphorus and iron content of the aeration solids to about 4% and 10%, respectively, apparently critical levels, along with a continuing mol dose of as high as 1:1, Fe/P (Re, Aeration Solids, TSS and % P and % Fe, Table V; also Columns 3 & 4, Table VI).

It is noted--Table VI, section on P Removal, Effectiveness and Efficiency--that phosphorus removal across primary clarifiers was nil to negative. Wasting of aeration solids (MLS) to primaries effected, marginally, a measurable reduction of soluble phosphorus across primaries, but, most of the time increased the suspended phosphorus content of primary effluent. The mass of the waste solids settled rapidly with some augmentation of removal of raw solids. But there was partial deflocculation of the waste sludge, and reflocculation was poor, resulting in carry over of fine to lightly flocculated solids across the short length effluent weirs. The phosphorus content of these solids was high, and COD low, as compared to raw solids, thereby keeping net removal of total phosphorus low to negative, but not significantly affecting COD removal across primaries.

There was little evidence that injection of iron to the aeration process gave appreciable augmentation of overall treatment effectiveness. It was possible to accept larger proportions of infiltration flow, without

loss of solids to effluent. When doses were sufficiently high to attain 75% or more removal of phosphorus, settleability of aeration solids was good, as indicated by sludge volume index values (Re: Aeration Solids, SVI, Table VI; also TSS and COD values). But through-plant removal of suspended solids and COD was only marginally better under comparable flow, loadings and operation control, than when no cations were added to primary or aeration processes. Dosing of iron to primary effluent was slightly less effective in COD and solids removal than dosing of iron to raw influent (Compare relevant control and index parameters, Tables I-III and V-VII).

Ferric and Ferrous Iron to Raw Influent

Two points of injection were tried for dosing Fe(III) to raw influent: in the wet well close to the pump suction; and to the outfall of the degritter chamber just ahead of the Parshall flume. Neither gave an adequate quick mix, in that there was appreciable hydrolysis, and precipitation before the dosage was homogeneously mixed. Dosing was for 13 days in February and March, 1969, during prevailing wet weather flow; and 20 days December 5-15, 1969, and December 24, 1969, to January 1, 1970, (Tables VII-VIII), during a period of decreasing wet weather flow and increasing influent phosphorus concentration. No opportunity was afforded at dry weather flow, of highest phosphorus concentration. Diurnally, all Fe(III) injection was at single-level rates.

There were two advantages of the wet well injection point over the degritter outfall point. First, it was easier to estimate and apply a desired mol dose to the total flow than to only the through-plant flow at time of any by-pass flow. Second, by injecting into the total flow, any

by-pass flow received an effective phosphorus insolubilization dose of iron, rendering such by-pass portions of phosphorus less readily available for promotion of organic growth in receiving waters.

In addition to experimental periods of dosing Fe(II) and Fe(III) to the wet well and degritter points of injection, Fe(II) was conveniently injected into a manhole about 300 ft (93 m) up-sewer from the plant lift station. For these three points there were no discernible differences in progression of reactions or in through-plant removal of phosphorus. There was essentially no precipitation and flocculation of ferrous iron, nor of oxidation to, and precipitation of ferric iron, until long after homogeneous mix of the dosage, i.e., after entry to primary clarifiers.

Fe(II) was dosed to the raw influent 54 days, March to June, 1969, including uninterrupted feeding May 1 through June 13; then, for 8 days, December 16-23. Diurnal dosing was at single-level rate except for 17 days, May 1-17 (Table V). Prevailing variable rainfall afforded demonstrations at an extremely low phosphorus level of only 2 mg/l (Table V, May 15-18), and up to slightly above 9 mg/l, December 16-23 (Table VII, Column 12, December 16-23), but not at 12-14 mg/l of dry weather flow.

Daily values of various parameters are listed in Table V and represented graphically in Figure 9, for dosing of Fe(II) through the month of May. Bi-hourly variations are represented graphically in Figures 10-12, for May 12 and 28, and June 3. Average doses, raw and effluent phosphorus levels, and phosphorus removal and insolubilization are summarized in Table VIII, for 7 representative incremental dosing periods of Fe(III), and 6 for Fe(II). These data are compared with data for other parameters in Table VII.

Again, as for the periods of feeding Fe(III) and Fe(II) to primary effluent, operation parameters were not wholly comparable from period to period, but sufficiently so to demonstrate that feeding of Fe(II) to raw

influent, at or ahead of the wet well afforded most effective and efficient utilization of iron. Mol doses of 1.3/1 to 1.6/1, Fe/P, consistently effected more than 80% removal, approaching 90%, even at single level diurnal dosage rates, (Table VIII, Summary Comparisons). Effectiveness was appreciably better than by feeding Fe(III) to primary effluent or to raw influent, and marginally so than by feeding Fe(II) to primary effluent.

Removal of phosphorus across primaries by Fe(III) was above 10% for only 12 of 33 days, and by Fe(II) was nil to negative except 8 of 39 days (Table VIII, Section, P Removal; also, Section Flow, MGD). There was visual and analytical evidence of precipitation of ferri-phosphate from the Fe(III) dosing, but very little sedimentation except at diurnal periods of low flow. The carry-through of deflocculated waste sludge also kept net removal at low levels. The 15-26% removal, December 13, 1969, to January 1, was attributable to decreasing through-plant flow, including diurnal low flow, 1-4 hours of less than .4 MGD rate; and to a change in sludge wasting process, after December 19, i.e., using one of the clarifiers solely as a thickener for waste aeration solids, MLS, thereby preventing carry-through of waste solids.

Dosing of Fe(II) to raw influent resulted in appreciable precipitation, flocculation and sedimentation of ferro- or ferri-phosphate only at diurnal periods of low flow, still carrying some infiltration water having sufficient DO to oxidize some of the Fe(II). These flow conditions prevailed in the period of December 16-23, when there was 20% removal across primaries, (Column 12, Table VII). Also, operation of one of the clarifiers solely as a sludge thickener kept carry through of waste solids essentially to zero.

It is noted that the analytical data for suspended solids in raw influent and primary effluent indicate for most of the demonstration periods, very little removal to heavy increase in solids across primaries. This was

attributable in part to carry-through of waste solids, but principally to precipitation of iron in samples in the interim between collection and assay, upwards of 24 hours, thereby giving a false indication (Table VII, Section, TSS; Re, also Section, Flow, MGD). There was visual evidence of removal of raw solids across primaries, also, of precipitation and sedimentation of iron, but no feasible procedure was found for routine measurement. Also, it is noted that removal of COD across primaries was quite low for 9 of the 13 demonstration periods. Highest removal was only about 30% (Table VII, Section, COD, Columns 3, 5, 12 and 13). At no time did dosing of Fe(III) or Fe(II) to raw influent show significant augmentation of removal of raw solids or COD, across primaries.

Overall treatment control and effectiveness with iron treatment, with respect to removal of COD and suspended solids, was better than with no added cations, but only marginally demonstrable. The principal advantages were: first, accepting more infiltration flow through the plant without loss of solids to the effluent; second, with injection of iron into raw influent, affording a phosphate precipitating dose to any by-pass flow; and third, retention of removed phosphate with the digested solids, minimizing recycle to primary and aeration processes. Iron treatment, particularly with injection of Fe(II) to raw influent, afforded an "ironing-out" effect to overall operational control and treatment effectiveness.

Sludge Production, Digestion and Dewatering

Wasting of the ferri-phosphate sludge to the primaries inhibited anaerobic action and facilitated withdrawal and pumping of the combined waste and primary sludge. Convenient scheduling of pumping was 1000-2000 gallons for each 8-hour operation shift, totaling about 5000 gallons (19 cu m) per day,

equivalent to approximately 1% of lowest dry weather flow of plant influent. Solids content of the combined sludge was 20,000-30,000 mg/1, about 50% ash. At 1.0 to 1.6 mol doses of iron Fe/P, total daily production was 800-1000 lbs (365-455 Kg), (Table XIII, Representative Sludge Production). Materials balance measurements and calculations gave no indication of greater or lesser production of organic solids than when no cations were added to primary or aeration processes.

The combined sludge digested and compacted effectively (Figure 18, Profiles of Digester Solids). Reduction of Fe(III) to Fe(II) was complete but over 95% of the phosphorus remained with the solids. Draining, cracking, and drying was rapid and effective, favorably comparable to that for non-ferri, non-phosphate sludge. The dried sludge contained 4-5% total phosphorus (90% fertilizer-available) and 10-14% Fe. Total N_2 by Kjeldahl was .6%. The sludge was utilized for fill and soil conditioning at plant site and adjacent areas.

Drainbed Digesting and De-watering of Waste Aeration Solids

For 12 days, May 18-29, 1969, the total wasting of aeration solids was directly to an 1850 ft^2 (174m^2) section of the sludge drain beds, 1/8 of the total area (Table V, May 18-29). In this period aeration solids were being maintained at highest levels, 3350-4200 mg/1. For the first four days aeration mixed liquor was wasted at 10-30 gpm (38-104 1/m). Then, as the wasting rate exceeded draining rate, return sludge instead of mixed liquor, was wasted at 5-15 gpm for 8 days. Water level on the bed did not rise to a fixed 12-inch overflow depth until the sixth day of the 12-day period. Solids subsidence and compaction was rapid, permitting essentially no loss of solids to overflow. Deposition was at about a 10-inch depth

at influent and about a 3-inch depth at overflow end of the bed at time of discontinuation of the wasting. Active anaerobic digestion had developed but the supernatant liquor and algal growth prevented escape of odors. Within five days after interruption of wasting, compaction was to about six inches and two inches at influent and overflow end respectively. Surface cracking had extended to considerable depth. Heavy algal growth had developed. But anaerobic digestion had progressed to odor nuisance level. The bed was then flooded with plant effluent, and the flooding repeated every 5-8 days. This permitted digestion to proceed to completion within about 30 days, with no odor nuisance. Then, after about 10 more days, with no retarding rainfall, the digested sludge had drained and dried to a readily removable condition. Thus, within a 2-month period, 12 days of waste aeration solids were digested and dewatered on 1/8 of the plant drain bed area. The dried solids were highly friable and contained about 5% phosphorus; over 90% fertilizer available.

LIMITED LIME TO RETURN SLUDGE
THEN TO RAW INFLUENT

Occasion and Premises

Menar and Jenkins have demonstrated the precipitation of calcium phosphate in activated sludge from high calcium wastewater (14), attributing the precipitation to increase of pH from stripping out of carbon dioxide by aeration. Emperical evidence was the increased calcium uptake from the substrate and increased calcium content of activated sludge, with its concurrent increased uptake and content of phosphorus. Correlation of uptake of magnesium was not observed. They pointed to calcium phosphate precipitation as a plausible accounting for high removal of phosphorus at the San Antonio, Texas, plants, observed by Vacker, et.al. (6) and by Witherow, et.al. (11).

The correlated uptake of phosphorus and calcium by activated sludge observed by Menar and Jenkins was from wastewater of approximately the same calcium and magnesium content as the San Antonio wastewater, i.e, about 90 mg/l calcium and about 20 mg/l magnesium. But the co-uptake occurred at appreciably higher pH than the experiential levels of 7.7-7.9 for the even higher uptake of phosphorus at the San Antonio plants. Since the studies at San Antonio did not include demonstration of the extent of uptake of calcium and magnesium, it was decided to measure co-uptake of phosphorus, calcium and magnesium by activated sludge at the Texas City plant. The calcium and magnesium levels in the Texas City wastewater were only about 1/2 those of the Sam Antonio wastewater, and the aeration effluent pH was within a slightly lower range, ie, 7.5-7.8 as compared to 7.7-7.9. It was considered, therefore, that it would be necessary to increase calcium and magnesium content and/or raise pH level, eg, by adding lime, in order to demonstrate significant precipitation of calcium or magnesium phosphate.

Limited Dosing of Lime to Return Sludge

For five days, July 15-19, 1969, lime slurry was injected to the bottom of the return sludge sump, near the point of pump suction. Doses were limited to amounts that would raise pH of aeration influent mixed liquor to above 8.0 but no higher than 8.5, expecting incipient precipitation of calcium phosphate, without significant change in bioactivity of the activated sludge. Experiential mol doses--mols of lime per mol of phosphorus in the raw influent--were 1.7, 4.2, 3.8, 3.4 and 2.1 for the respective five days (Table IX). Aeration influent pH levels of 8.1-8.4 fell to 7.6-7.9 through aeration. Calcium content of aeration solids increased from 2% to about 5%, but there was no measurable increase in

phosphorus or magnesium content. Daily phosphorus removal averaged 19% as compared to 15% and 12% respectively in the 5 preceding and 9 succeeding days, with no addition of lime. Settleability of aeration solids as indicated by the SVI test, was better, and the improvement extended for several days after withdrawing lime treatment. However, effluent suspended solids were not reduced below the 6 mg/l average level being attained with no added lime.

Dosing of lime to return sludge was interrupted after five days. Extension of the treatment to higher dose levels had been planned, even at the risk of imposing upsetting changes of bioactivity in aeration. It was decided not to take this risk until further observations could be made without and with lime and other cations added to raw influent and primary effluent. These Project priorities held precedence and opportunity was not afforded for further experimentation with injection of lime to return sludge.

Lime to Raw Influent

For 8 days, July 29 to August 5, 1969, lime slurry was injected into the plant wet well at a point near the suction of the lift pumps. Doses were objectively limited to partial precipitation of calcium phosphate in primaries, controlling at levels that would result in carry-through of precipitation, and raise the pH of the aeration influent mixed liquor to no higher than 8.5. Dosing was discontinued when it became evident that excess precipitation of "lime" sludge in the primaries might impose upsetting changes in sludge digestion.

The incremental mol doses of lime were from 2.2 to 8.4, Ca/P (Table IX). Primary effluent pH levels were raised to a range of 8.30-9.15, aeration influent levels to 8.10-8.40, and aeration effluent levels

to 7.60-8.05. There was no measurable increase in phosphorus, calcium or magnesium content of aeration solids. Through-plant removal of phosphorus reached as high as 42%, but practically all the removal was registered through the primaries. Sludge volume index values were high but effluent suspended solids remained low. Effluent COD was very low, averaging 21 mg/1 as compared to about 30 mg/1 in the previous 29 days. There was no discernible effect on sludge digestion by the "high lime" primary sludge.

ALUMINUM CHLORIDE TO RAW INFLUENT AND TO PRIMARY EFFLUENT

The objective was to demonstrate dosage requirements of aluminum for 80-90% removal of phosphorus, when injection was into the raw influent, and when into the primary effluent. Aluminum chloride solution was used, a waste by-product in polystyrene manufacture, supplied by the Monsanto Company, Texas City, Texas. It contained 5 to 6% available aluminum and less than 1% free acid. There were no contaminants known to be inhibitory to bioactivity. Injection was to the raw influent for 18 days, August 21 to September 8, 1969, and to the primary effluent for 37 days, September 9 through October 15, (Tables X-XII; Figures 1, 14-17). Diurnal dosing rates were two-level, September 3-23, but at single-level for the remainder of the time.

Dry weather prevailed except for light to moderate rainfall August 21-29 and October 9-13. Total flow was accepted through plant except for only 70 to 80% for the first three days, August 21-23, and for August 28, 29, and 31.

Digester supernatant and drain bed liquor were regularly recycled to

the raw influent. Aeration sludge return rate was about 100% of dry weather plant flow. Aeration solids, MLS, were wasted to one primary, used solely as a thickener for the first 8 days, August 21-28. For the remainder of the time return sludge was wasted to both primaries, used as clarifiers for raw influent. Aeration solids ranged from 1500-3000 mg/l, with indications that 2000-2400 mg/l was optimal. Air application was at maximum rate during diurnal high loading periods for maintaining measurable DO in the aeration effluent, and at sufficient rate through low loading periods to effect a daily average of 1.0-1.5 mg/l, experientially indicated required levels for best solids conditioning and maximum removal of COD and suspended solids.

Daily averages of operation and index parameters are listed in Table X. Averages for the 10 incremental dosage periods are listed in Table XI, and summarized in Table XII. Averages, weighted proportional to flow, are shown for periods when variations in flow imposed significant differences. Representative around-the-clock variations for flow and for raw and effluent phosphorus, at two dose levels, Al/P, are shown graphically in Figures 14 and 15. Daily averages, August 8 through October 12, for flow, aluminum doses, effluent COD and suspended solids, and for raw and effluent phosphorus are shown graphically in figures 16 - 17.

Dosage to Raw Influent

Aluminum chloride was injected into the plant wet well, near the lift pump suction, August 21 through September 8. Each daily dose was fed at a single level rate through September 2. Then, September 3-8, daily doses were fed at a two-level rate; during the low load period for about six hours, approximately proportional to the average phosphorus level; and the remaining time, at a rate approximately proportional to the higher average phosphorus loading.

After an initial period of 3 days, in which dosage was increased from .46/1 to 1.23/1, Al/P, an attempt was made to hold at a fixed dose through at least five days. This was not found to be possible. But in retrospect, an average daily dose for a period of 4 to 8 days was designated as the incremental dose for the period, in that it was not greatly different from the high or the low on more than one day. Thus, there were three incremental dose periods when injection was to the raw influent: 1.25/1, Al/P, August 24-27 and 2.04/1, August 28 to September 2, dosed at single level rates; and 1.79/1, September 2-8, dosed at two level rate.

Through-plant removal of phosphorus at these three doses was 68%, 69%, and 74% respectively, and insolubilization of phosphorus was 70, 71, and 77%, (Tables X-XII). There was no removal of phosphorus through the primary units at the lowest dose, August 24-27, which was attributed to the use of only one primary as a clarifier, and to carry-over of de-flocculated alumina-phosphate solids from the clarifier being used as a thickener for waste aeration solids. With the use of both primaries as clarifiers, and wasting of aeration solids to both, August 28 to September 2, phosphorus removal through primaries was 30% and 40% for the respective doses of 1.79/1 and 2.04/1, Al/P (Table XI, section, P removal). Dosage efficiency was best at the lowest mol dose, 1.25/1, Al/P, affording an effective mol ratio for removal of 1.84/1 (EMRr, mols of Al to mols of P removed), and for insolubilization, an effective mol ratio of 1.79/1, (Table XI, Effective Mol Ratios, EMRr and EMRi). Efficiency was quite low, EMRr of 3.14/1, at the mol dose of 2.04, with diurnal dosing rates at single-level. The two-level mol dose of 1.79/1 was more efficient, EMRr and EMRi, 2.42/1 and 2.32/1, respectively. But it was evident from these

limited demonstrations that more effective, quick mix of dosage, much more rigid proportional feeding and more effective flocculation would be required for efficient utilization of aluminum chloride, when injection was to the raw influent.

Dosage to the Primary Effluent

From September 9 through October 15, 1969, aluminum chloride was injected into the primary effluent at confluence with return sludge (Figure 1). Through September 23, diurnal dosage rates were two-level; after that, at single-level.

The first incremental dose of 1.65/1, Al/P September 9-13, effected 81% removal and 84% insolubilization of the phosphorus load (Tables X-XII). The two sequential incremental doses (at two-level rates), 2.02/1 and 2.41/1, September 14-18 and 19-23, removed 82% and 80% and insolubilized 87% and 92%, of phosphorus loads, respectively. The next incremental doses, fed at single-level rate, September 24 to October 1 and October 2-6, were 2.41/1 and 2.20/1. Phosphorus removal was 80% and 82% and insolubilization 92% and 92% respectively. A subsequent dosage period, of widely varying doses, averaging 2.21/1, effected only 68% removal of phosphorus , but insolubilized as much as 92%.

Dosing of aluminum chloride was more efficient when injected to primary effluent than to raw influent. But, even at two-level rate, daily mol doses of 1.6-1.8 were required to attain 80-85% removal of phosphorus. Higher doses gave no increased removal. Insolubilization reached a peak of slightly above 90% at mol doses of 2.0/1 to 2.2/1.

Wasting of the alumina-phosphate aeration solids to primaries effected only 5-10% reduction of soluble phosphorus. Net removal of total phosphorus

across primaries was negative, attributable to deflocculation of the sludge with resultant carry-through of high phosphate solids (Tables X and XI). Wasting of the solids to primaries effected no measurable increased removal of influent COD and suspended solids.

Through-plant removal of COD and suspended solids was at about 90% and 95% respectively for aluminum doses, Al/P, up to about 2/1. At higher doses removals were as low as 80% and 75% respectively, attributable to inadequate flocculation, resulting in high effluent solids (Tables X and XI and figures 16 and 17). Aeration pH levels were reduced to as low as 7.0-7.2, at the high aluminum doses, concurrent with the poorer flocculation and higher effluent solids (Table XI).

Polyelectrolyte Coagulant Aid to Aeration Effluent

Demonstration results pointed to the need for the following: more rapid mix of the aluminum chloride dose; rigid proportional feeding, Al/P; adjustment of pH level; addition of a coagulant aid. Opportunity was afforded only for demonstrating the effects of adding a polyelectrolyte coagulant.

For four days, October 7-10, a cationic polyelectrolyte (ST-260, Calgon Corporation) was dosed to the aeration effluent at 1 mg/1, proportional to plant influent flow (Tables X-XII). The average aluminum dosage was 2.56/1, Al/P. Effluent solids averaged 6 mg/1. Phosphorus removal was 90% and insolubilization was 92%. Since insolubilization of 92% was attained at the lower aluminum doses of 2.2/1 to 2.4/1 (Columns 7-10, Table XI), 90% removal might have been attained had the polyelectrolyte been used; also as much as 95% removal of suspended solids.

Sludge Production, Digestion and De-Watering

Wasting of the high alumina-phosphate solids to primaries gave a

combined waste and primary sludge of 1.5-2.0% solids, dry weight basis, containing about 40% ash (Table XIII). Sludge pumping was conveniently scheduled at about 2000 gallons each, for the three 8-hour operation shifts, totaling 6000-7000 gallons per day (23-27 cu m per day); this, without development of objectionable digestion in primaries.

Digestion was moderately rapid in the digesters, but compaction was only to about 2.5% solids (Table XIII and Figure 18). This limited digestion time, and entailed frequent drawing of "green" sludge. Draining on the sand beds was slow, but digestion continued to completion within 10-15 days, without development of odor nuisance. After about 10 more days, dry weather permitting, draining, cracking and drying, had proceeded sufficiently for ready removal by a "spade-fork-truck" procedure. Upon re-wetting and drying the solids were quite friable. The solids were utilized for fill and soil conditioning in the treatment plant area.

DISCUSSION

Treatment control efforts were for maximum removal of COD, nitrogen, phosphorus and solids, pointedly, for building, removing and disposing of solids of high phosphorus content. Key control parameters were those of materials balance considerations in production and management of solids. For some of these, correlations with phosphorus removal were closely measurable, eg., the added, and some of the influent cations, and the phosphorus and cation content of aeration effluent and digested solids. Interrelated effects often obscured individual effects. Discernible effects and correlations afford guidance to interpretation of results and point to means for more effective treatment control.

REMOVAL BY ACTIVATED SLUDGE
NO ADDED CATIONS

Model for Processing

In prospect and retrospect, proposed premises for removal of phosphorus by activated sludge included (6):

First, building of cell solids by microbial species capable of biological phosphorus enrichment (7, 8, 9, 39).

Second, sufficient nutrients for, and actual building and removing of sufficient high phosphorus solids, eg, for 90% removal of 10 mg/l of phosphorus by the building and removing of 180 mg/l of solids containing 5% phosphorus.

Third, phosphorus enrichment of cell solids occurs in the nutrient imbalance or deficiency conditions (7, 8, 9) of declining growth and endogenous phases and not when there is sufficient nutrients to promote, predominantly, log growth of cells.

Fourth, aeration at least to measurable DO is necessary for promotion of phosphorus enrichment.

Fifth, anoxic conditions, and/or resupply of nutrients promote release of phosphorus enrichment (2, 6, 13).

Sixth, extended aeration or anaerobic digestion releases most all of the biologically contained phosphorus (6, 38).

Process and Operational Limitations

Biological Enrichment, Species Specific -- The first premise affords, plausibly, a principal explanation of the very low phosphorus removal when there was no phosphorus enrichment of solids (Table III). During these 73 days, over 700 samples of aeration mixed liquor, return sludge and waste sludge were analyzed for total and soluble phosphorus, the soluble phosphorus assay being made on filtrates procurred at time of sample collection. Also, soluble phosphorus analyses were made on 73 24-hour composites plus 130 bi-hourly grab samples of plant effluent. The lowest observed level of soluble phosphorus was 6.2 mg/l, this, in a stream of flow in which influent total phosphorus had been only 8 mg/l. At no time was there indication of more than 25% through-plant uptake of phosphorus. The weighted average removal for the 73 days was 13.1%. The phosphorus content of aeration solids, when there was no residual ferri- or alumina-phosphate from previously added cations, was never as high as 2% (Table III, %P in Aeration Solids).

No attempt was made for identification of microbial populations, to see if predominant species included those demonstrated to have biological phosphorus enrichment capacity (8, 9). But, whatever the predominant species of aeration processes during the 73 days, (Table III), there was no phosphorus enrichment. Therefore, it is assumed that such species were absent, or always at very low population levels.

The hypothesis that biological phosphorus enrichment is species

specific, points to an explanation of the variable and ever decreasing phosphorus removal June, 1968, to January, 1969, (Table II, Re sequential data for flow and % P in Solids; also, Table I). For each heavy infiltration, high flow period there was, not only some loss of aeration solids, but more seriously, a loss of phosphorus enrichment of solids, followed by a lower rate of re-enrichment. In the very heavy and frequent high flow periods of December and January, there was complete "wash out" of enrichment, and apparently of re-enrichment capacity. If biological phosphorus enrichment is species specific, this could have been a "wash out" of the species.

Materials Balance Requirements--The second premise above, along with phosphorus enrichment capacity of cell solids, point to another limiting factor to high phosphorus removal at the Texas City Plant #2, and similar plants treating similar sewage, ie, plants and processes of equivalent solids building capacity. In the 15-day period, August 10-24, 1968, (Table I and Figure 3a), flow and sewage characteristics were representative of dry weather conditions. Primary clarification was not being applied, affording representatively highest COD entering aeration processes at highest COD/P ratio, conditions favorable for maximum building of solids and biological uptake of phosphorus (1, 6) (Tables I, II, & III, COD and COD/P data). Operation control was near experiential best. The average flow was .388 MGD (1470 cu. m) and average removal of phosphorus was 4.8 mg/l, or 43% of the 11.1 mg/l influent phosphorus. Average phosphorus content of aeration solids was 3.5%. The average measured wastage of solids of this phosphorus content was 450 lbs/day (205 Kg/day) equivalent to 139 mg/l in the .388 MGD flow. For 90% removal, it would have required a net building and wasting of 922 lbs/day (420 Kg/day), or 285 mg/l in .388 MGD flow. If phosphorus enrichment of the solids

had been at 5%, about the highest experienced at the Texas City Plant, it would have required net building and wasting of 200 mg/l of solids, for 90% removal of phosphorus. This 200 mg/l solids building-wasting level is considerably above experiential levels, attributable to the limiting nutrient(COD) level of influent sewage, and to somewhat extended aeration, resulting in digestion of some of the solids built.

Complete Mix Aeration; Variations in COD and P Loading; Air and Solids Management--There were three closely interrelated operational factors limiting to phosphorus removal through biological enrichment of aeration solids: first, the near complete mix of the aeration units; second, the extreme diurnal variations in COD and phosphorus loading, characteristic of small treatment plants; and third, cell destruction, resulting from the aeration solids management--high sludge return rate, moderately high aeration solids level (MLS) and sludge age, and the high rate of air application--all, experientially essential for maintaining effluent BOD_5 and suspended solids at desired low levels.

These operation conditions are in contrast to those of large plants having very long, "plug flow", aeration tanks, also, having fine bubble air diffusion , and greater flexibility in air application and solids level control, eg, the San Antonio, Texas, plants (6, 13). In line with the model--the six premises above--progression of solids building and phosphorus uptake in such "plug flow" systems is envisioned as follows. Log growth of cells is predominant through an entrance segment of aeration until substrate utilization is near complete, with uptake of phosphorus limited to requirements for cell multiplication (1, 2, 6). Then, in extended segments of aeration distance and time, in declining to endogenous bioflocculation phases, with nutrient imbalance, the cells store phosphorus to the extent of their enrichment capacity or to

depletion of substrate phosphorus. As high as 7-8% phosphorus in aeration solids, and substrate depletion to less than 0.1 mg/l have been observed (6, 38). Dissolved oxygen levels above 1 mg/l are favorable for rapid and complete uptake of phosphorus, but recently, Wells (38) has demonstrated high uptake at DO levels no higher than 0.2-0.3 mg/l. Aeration to higher levels in the effluent end of aeration aids in preventing anoxic release of phosphorus through clarifiers and in return sludge, but extended aeration promotes digestive release of phosphorus. With entry of "plugs" of mixed liquor--return sludge, plus influent with a fresh supply of nutrients--there is release of phosphorus enrichment. Higher than 30 mg/l soluble phosphorus in entry portions of aeration units, have been observed, 2 to 4 times higher than soluble phosphorus levels in the influent or return sludge (6, 38). But as the "plug" moves through the log growth substrate utilization phase into the declining growth bioflocculation phase, there is re-uptake of the released phosphorus; then, in flow cycles, sequential uptake of phosphorus, wasting of some of the high phosphorus solids, but return of sufficient viable cells and of nutrients for building and removing of more cells of high phosphorus enrichment.

This phase progession for efficient building and removing of high phosphorus solids cannot be attained in small systems such as the Texas City Plant #2, with its short length aeration units of turbulent aeration, receiving highly variable loadings. Equilibria may be envisioned through limited periods of effective uptake and removal. And, evidently, such did occur for net removal, through 24 hours, as high as 70-80% (Figures 4 and 5), and in 3-day periods, 50-70% (Figures 2, 3a, 5 and 7; and Tables I and II). But on days immediately preceding

and succeeding, there were shifts to heavy release or lesser uptake, resulting in low net removal. Note time-peak-trough patterns: Figure 2, June 3-5; Table I and Figure 3a, August 13-18; Figures 3 and 4, September 24-October 1; and Figure 4, October 1.

In jar tests on grab samples of aeration influent mix liquor it was possible to demonstrate anoxic release of phosphorus and/or release by the fresh supply of nutrient COD; to levels 10-15 mg/l above soluble phosphorus levels in the influent or return sludge; then, aerobic uptake to residual levels below 1 mg/l. But in the near complete aeration mix of the plant, such levels of release were not registered, and only infrequently were such low residuals from uptake registered. Net effects were reflected in the 8- to 12-hour time-volume flow-through patterns.

On June 3, 1968 (Figure 2), effluent phosphorus fell from 3 mg/l to 0.1 mg/l, 12:00 a.m. to 6:00 a.m. then rose to 1.2 mg/l by 8:00 a.m., and held at . mg/l until 12:00 noon. In the preceding 8-12 hours, influent phosphorus had been at 6-8 mg/l (June 2, not shown in Figure 2). Thus, for the reduction of this 6-8 mg/l to 3 mg/l, then to 0.1 mg/l, equilibria evidently were favorably "on the uptake", for a net removal of 75%. Or, during the low flow period through 8:00 a.m., with decreasing loadings, there was an approach to "batch treatment", favorable to completion of the log-growth substrate utilization phase, with "nutrient starvation of cells" (7, 8), and permitting extension into the declining growth endogenous phase, for high-rate uptake of phosphorus. But the increasing flow 8:00 a.m. to 12:00 noon, June 3, with its heavy load of COD, imposed negating release of phosphorus enrichment, registering lower net uptake. The flow-through patterns of influent COD and phosphorus loadings, and of effluent phosphorus, June 4-5 (Figure 2), reflect

further cycles, from effective to low, to even negative uptake of phosphorus, attributable primarily to variations in COD and phosphorus loadings. But note also the cause- effect relations of air application and DO levels (Figure 2, G, DO in Aeration Effluent). During these three days, air application was held near constant rate. With decreasing loadings, DO in the aeration effluent rose and held at a slightly higher level until the effects of increased COD had extended through aeration units. It is also noteworthy that DO ranged from 0.2 mg/1 to no higher than 1.3 mg/1, evidently, levels sufficiently high for effective substrate utilization (Figure 2, D, COD in Final Effluent), and for promoting high uptake of phosphorus. It appears also--COD and solids loadings permitting--that this DO range is optimal for minimizing aerobic digestive release of phosphorus.

The variations in phosphorus uptake, normally reflected from regular diurnal variations in COD and phosphorus loadings, were also affected by changes at irregular intervals and to other factors. The increase in effluent phosphorus 2:00 to 10:00 p.m., August 14 (Figure 3a)--a decreasing net uptake--was due primarily to high influent phosphorus, from a non-discerned source, 27 mg/1 in the 2:00 p.m. sample. The low profile of removal August 25 to September 3, 1968,(Table I and Figure 3) was attributed first, to anoxic release of phosphorus from solids in the secondary clarifier, due to slow rate of withdrawal and return, practiced for several days; and second, to aerobic digestive release (Note DO and nitrate levels Table I). The very low profile of phosphorus removal, September 3-23, including extreme variation, was attributed to "wash out" of phosphorus enrichment by high flow, bringing not only surges of phosphorus-releasing COD from sewer-flushing

first rises, but also inorganic and silt dilution of phosphorus in the aeration solids. Note (Table I and Figure 3, % P in Aeration Solids), that phosphorus content of aeration solids ranged down to as low as 1.5%, and did not recover to 3% until September 21. The very low net uptake of phosphorus October 5-6, was also attributable to a slug of COD from rising flow, reducing phosphorus in solids from 4% down to 3%, and reducing net removal to 9% (Figure 5). Then, for three days with uniform flow of about 1 MGD, (3,790.cu m/day), even with wide variations in COD and phosphorus loadings, net uptake was high and daily average removal, 70%. But the very heavy infiltration flow late October 9 through 10, produced a "wash out" of phosphorus enrichment.

The very low phosphorus content of aeration solids and resultant low through-plant removal, November 18-20 (Figure 6) was due primarily to anoxic release of phosphorus from solids retained in and moving through secondary clarifiers, but in part to aerobic digestive release.

Air application was heavy in the previous 3-4 days, in an attempt to overcome anoxic conditions in the clarifiers. Operation without primary clarifiers (August, through November 26, 1968) plus silt-bearing influent had resulted in build-up and deposition of "raw debris". These accumulations were removed by auxiliary intermittent aeration of the clarifiers and rapid withdrawal of solids, November 15-19. Phosphorus content of aerations solids built rapidly back to above 2.5% for higher removal November 24-26 (Figure 7).

Through December, 1968, to January 19, 1969, phosphorus content of aeration solids could not be maintained above 2%, because of frequent and heavy infiltration flow. Phosphorus removal deteriorated to levels experienced when there was no enrichment of solids (Table III).

Digestive Release of Phosphorus--Another process factor limiting to the removal of phosphorus was digestive release through extended aeration. The lysing of cells releases not only phosphorus of enrichment, but almost the total of biological uptake. Degree of nitrification is pointed to as an index (Tables I-III, Nitrogen Section. Compare degree of nitrification and denitrification before and after December, 1968). Vacker, et.al (6) and Witherow, et.al (13) have noted reduced phosphorus removal by extended aeration and nitrification.

Again, it is noted that loss of phosphorus enrichment of solids, and of enrichment capacity in December, 1968, and January, 1969, (Table II) was attributed to frequent and heavy infiltration flow. But aerobic digestive destruction of cells and release of phosphorus was contributory to this loss.

In the demonstration periods, June to November, 1969, with no added cations, aeration and nitrification was even more extended than in December,1968, and January, 1969. And this, along with other process differences as follows, is believed to have been contributory to the absence of phosphorus enrichment and the very low phosphorus removal.

Dry weather flow prevailed. Total flow was accepted, which, even with primary clarifiers in service, brought heavier daily COD and phosphorus loadings to aeration, and sharper diurnal variations in loadings. Aeration solids were held at about the same level, which, without primary solids, kept a higher inventory of cell solids--greater sludge age. Air application was at higher rates, holding DO at equivalent to higher levels, essential for maintaining low effluent COD and solids, but promoting nitrification and digestive destruction of solids. This was evidenced by the higher nitrate levels and lesser net production of solids.

For example, July 1-14, 1969, (Table III), nitrification was to a daily average of 6.2 mg/l nitrate nitrogen, 26 lbs/day; and measured wastage of aeration solids was .37 lb/lb of COD, a total of 416 lbs/day. Whereas, August 10-24, 1968, (Table I), nitrification was only to 0.6 mg/l nitrate nitrogen, 2.6 lbs/day, and net production of aeration solids was 0.45 lb/lb of COD, 456 lbs/day. Thus, the excessive destruction of cells, including those of phosphorus enrichment capacity, along with near total release of contained phosphorus would, in part, account for the non-enrichment of solids and the very low phosphorus removal June to November, 1969. Further, based on the experiential observations, but without presenting supportive speculative theory, it is suggested that nitrifying bacteria have low phosphorus enrichment capacity; and/or that the biochemistry of nitrification negates cell populations of high enrichment capacity.

Control and Index Parameters

It was concluded that in a small (0.7 MGD) activated sludge plant such as Texas City #2, with its near complete mix aeration and extreme variations in COD and phosphorus loadings, high level phosphorus removal is extremely difficult, if not impossible. But within the hyposthesis that phosphorus enrichment is species specific, and in terms of process premises (Page 48, above), experience points to process and parameter level requirements.

Materials Balance Requirements--There must be sufficient COD for building of sufficient solids of sufficiently high phosphorus content, eg, in the order of 360 mg/l COD, for building of 180 mg/l waste solids, of 5% phosphorus content, for 90% removal of 10 mg/l influent phosphorus.

Control of Solids Building by "Plug" Flow--The log growth substrate

utilization phase of cell production must be brought to near completion, then no resupply of food be permitted until phosphorus enrichment and uptake are at maximum, and the solids removed from aeration. This can be attained in long narrow "plug" flow aeration tanks.

Limited Solids Levels and Air Application--Solids level and aeration must be sufficient for high uptake of phosphorus, to promote bioflocculation and to prevent anoxic release in clarifiers, but limited to prevent excessive sludge age and aerobic digestion of solids.

Solids Management--Aeration solids must be moved through secondary clarifiers with minimum anoxic release of phosphorus enrichment and minimum loss of solids to plant effluent. Reaeration of return sludge must be limited to prevent extensive release of phosphorus by aerobic digestion. And excess solids cannot be wasted through primary clarifiers.

Solids Disposal--Disposal or utilization of waste solids must be without recycle of released phosphorus to primary or aeration processes.

Phosphorus and Magnesium Co-enrichment of Activated Sludge

To obtain information on calcium and magnesium uptake when no cations were being added, analyses were made on representative samples of raw influent, final effluent, aeration solids (MLS), return sludge and of waste sludge, July-December, 1968, when there was evidence of varying degrees of biological phosphorus enrichment of aeration solids. Then, July 10 through August 5, 1969, analyses were made when there was no evidence of phosphorus enrichment of solids, including 5 days when lime was added to return sludge and 9 days when lime was added to the raw influent (Table IX). Over 100 samples of aeration effluent (MLS) from the east aerator, over 50 from the west aerator (Figure 1), and over 100 samples of return sludge and waste activated sludge were analyzed for total and soluble phosphorus, calcium and magnesium. Assay for soluble components was made on filtrates procurred at time of sampling.

Variations in calcium and magnesium content of the raw influent were of such proportions, frequency and irregularity as to preclude precise measurement of uptake from influent to effluent. But sampling of aeration solids was sufficiently representative and analyses sufficiently accurate and precise to measure changes in magnesium, and calcium content of aeration solids. There were increases in magnesium content, but not of calcium, somewhat in proportion to increase in phosphorus content.

The data for 109 samples of mixed liquor (East aerator effluent), including samples of July 11 to August 3, 1969 (Table IX) were plotted: first, Figure 13b, % phosphorus in solids (X) and % magnesium in solids (Y); and second, Figure 13c, % phosphorus in Solids (X) and % calcium in solids (Y). For the phosphorus magnesium relation the linear equation of best

fit (A of Figure 13b) is Y= .2691 X - .1181; correlation coefficient, + .7674, at 1% level. Thus, it is indicated for each mol of phosphorus enrichment above 1.5% content of the aeration solids, there was uptake of about 1/3 mol of magnesium. For the phosphorus-calcium relation the linear equation of best fit is Y = 3.1583 - .5487X; correlation coefficient, -.3853. Thus, there is evidence that there was no increase of calcium uptake with phosphorus enrichment of aeration solids, and no significant evidence of release.

REMOVAL OF PHOSPHORUS FROM DIGESTER LIQUOR

Precipitation with Lime

The demonstrated lowest chemical cost for precipitating phosphate from digester liquor was $.12/lb of phosphorus removed. This was by use of hydrated lime when the phosphorus content of the liquor was 249 mg/l (Column 6, Table IV). At the optimal reaction pH of about 9.0 for reducing phosphorus level to below 10 mg/l, the effective weight ratio was 7.3/1, lime/P, for the precipitation of 242 of the 249 mg/l of P. For the 12,000 gal (45.5 cu m) 178 lb (81 kg) of lime was used for precipitation of 24.3 lbs (11 kg) of phosphorus. At $30/ton, ($36/metric ton) for lime this amounted to $0.12/lb of phosphorus removed ($0.26/kg).

The 249 mg/l phosphorus content of the liquor on September 27, 1969, was representative of production in the 12 preceeding days, when the weighted average daily uptake and removal of phosphorus by activated sludge was 17 lbs, 41% of the 42 lb daily phosphorus load. Materials balance measurements indicated that an average of 18.3 lbs of phosphorus was transferred to the digester daily: 5580 gal/day (21.3 cu m); containing 1.64% dry wt solids; of 2.4% phosphorus content--5580 x .0164 x .024 x

8.34 = 18.3 lbs/day (8.3 kg/day). The chemical costs for re-precipitation of the 17-lb net removal of phosphorus was $2.04 per day. Thus, for removal and disposal of 41% of a 10 mg/l phosphorus load in 1 MGD, the chemical costs would be $4.10/day.

Lime dosage efficiency improved with increasing phosphorus content of liquor. No opportunity was afforded for plant-scale demonstrations for liquor containing more than about 250 mg/l. But in bench-scale tests on liquor fortified to about 500 mg/l phosphorus, effective weight ratios of less than 5/1, lime/P (EWRr), reduced phosphorus to below 10 mg/l. On this basis, the chemical cost would be $08/lb of phosphorus removed. Then, if biological uptake and removal of phosphorus were raised to 82% as compared to the experiential of 41%, also, if waste sludge were thickened to the experiential 1.6% solids content, without significant loss of phosphorus enrichment--the chemical cost could be as low as $5.5/MGD. This is assuming 82% removal of a 10 mg/l (83.4 lb/day) in 1 MG, and $.08/lb of phosphorus removed--(.82 x 83.4 x $.08 = $5.50). Thus, the chemical costs for re-precipitation of the biologically removed phosphorus would be only about 1/4 the chemical costs for removal and disposal of 80-85% of phosphorus load by use of iron in primary and/or aeration processes, (Re: $22.50/MGD, Use of Iron in Primary and Aeration Processes, Discussion below). But it is again noted that this is on the basis of 82% uptake by activated sludge and release of the phosphorus in digester liquor to at least 500 mg/l. Further it is recognized that applicatory considerations hinge on the over-all feasibility and costs of the processes. These, in turn, hinge on equipment and operational costs for application of chemicals and for dewatering and disposing of solids produced.

Demonstration experience in re-precipitation and disposal of 17 lbs/day of phosphorus does not delineate, but affords guidance to feasibility and costs considerations for a 0.5-1 MGD operation.

Chemical Feeding and Mixing--Digester liquor production was about 6000 gal/day (23 cu m/day). Batch treatment was conveniently scheduled for 3-4 days of operation per week, 6-10 hours/day. Dry lime feeding, directly into the treatment stream through the 2-3 minute slurry box of the feeder, gave adequate mixing. Rapid deposition of magnesium ammonium phosphate on slurry box effluent orifices and transmission line entailed frequent cleaning. Substitution of the effluent pipe with an open trough, facilitated cleaning without interruption of operation.

Completion of Reaction and Solids Conditioning--The 30-50 minute gentle but near complete mixing in the 1200 gal (4.6 cu m) reactor tank, by air agitation, completed precipitation and solids conditioning, optimally at pH 9.0, with no further objectionable scaling or solids deposition. At higher pH levels there was excessive precipitation of non-phosphate solids, with hard scaling of transmission line. Transmission of the reactor mixed liquor--3500-5000mg/1 solids--through 2-inch and 2½-inch plastic pipe was without impairment to settling and draining of the solids.

Drain Bed Dewatering--Subsidence and draining on a 42 x 44 ft (14 x 15 m) section of sand drain beds were rapid. For prolonged runs, when influent rate exceeded draining rate, the clear supernatant overflowed to an adjacent section for draining, with essentially no accumulation of solids. Final draining, cracking and drying to a readily removable cake, 20-40% moisture, was fully as rapid and effective as for digested sludge from a mixture of primary and activated sludge solids.

Solids Production--Under best experiential operation--precipitation of 97% of 249 mg/1 phosphorus--solids production per pound of phosphorus removed was 0.15 cu ft of sludge cake of 60% solids content, and 15.3 lbs (7 kg) of dry weight solids (Column 6, Table IV). These values would probably be reduced by about 20% for precipitation of phosphorus from liquors containing as much as 500 mg/1. It is estimated for a 1 MGD operation with 80-85% removal and disposal of phosphorus, three drain bed sections of about 50 x 50 ft, totaling 7500 sq ft (67.5 sq m) would afford adequate drain bed capacity.

Solids Utilization--The solids contained 4-5% fertilizer available phosphorus. Best utilization was for spreading on acid soils deficient in phosphorus.

Precipitation with Iron and Aluminum

Effectiveness and Chemical Costs--In the limited plant-scale tests on digester liquor containing less than 100 mg/1 of phosphorus,mol doses of 1.3/1 to 1.5/1 Fe/P or Al/P, were required to reduce phosphorus to below 10 mg/1. In bench-scale tests on liquor fortified to 350 mg/1 phosphorus, mol doses of 1.3/1 to 1.5/1 also reduced phosphorus to below 10 mg/1, but only with the addition of about 1/1 mol dose of lime to hold end-point pH at 4.5-5.0 for iron and 5-5.5 for the aluminum dose. This entailed weight ratio doses of about 2.5/1, 1.2/1 and 2.5, Fe/P, Al/P and lime/P respectively. The market value for the "by-product" ferric chloride and aluminum chloride was $0.10 and $0.10 per lb of Fe(III) and Al(III) respectively. The market value for lime was $.015/lb. Therefore, the indicated chemical cost for each lb of phosphorus removed was $0.29 for use of aluminum. Thus, the use of iron or aluminum would not be competitive with the use of lime. But, again, applicatory considerations hinge on

overall feasibility and costs of processes.

Chemical Feeding, Flocculation and Dewatering--Equipment and labor costs for feeding iron or aluminum are significantly less than for lime. Costs of facilities and operation for flocculation and solids conditioning would be essentially the same. Dewatering of the ferri- and alumina-phosphate sludges, as for lime-phosphate solids, can be effectively dewatered by subsidence, decanting and draining on sand drain beds. But the order of drain bed requirements would be about 3:2:1 for the alumina-, ferri- and lime-phosphate solids respectively.

Dry Solids Production and Utilization--The final dry solids production for alumina-, ferri-,and lime-phospnate solids would be in the order of about 2:3:6. Best utilization of the alumina- and ferri-phosphate solids would be for spreading on phosphorus deficient soil.

REMOVAL AND DISPOSAL OF PHOSPHORUS BY USE OF IRON

Demonstration objectives were to obtain guiding information on effectiveness and economic feasibility of the use of iron in an activated sludge plant for removal and disposal of phosphorus, i.e., applicable answers to the following questions. Which is the better form of iron to use? Ferrous (Fe II) or ferric (Fe III)? Should dosage be to the raw, or to the aeration influent? How critical are the needs for quick mix of chemicals, and for rigidly proportional feeding? How different are control and index parameters for equivalent or better removal of COD, suspended solids and nitrogen? What are the dosage requirements for removal and disposal of 80-90% of plant phosphorus loads? Over what range of influent phosphorus concentrations? Does the iron hold the removed phosphorus with the solids

through digestion, thereby obviating the need for reprecipitating the phosphorus from digester liquor? What about the increased solids production and disposal problems? What are chemical and overall costs?

Fe(II) to Raw at Single-Level Diurnal Rates: Effective and Most Feasible

Dosage of Fe(II) to the raw influent at single-level diurnal rates was quite efficient, and the most feasible mode of treatment at the Texas City #2 plant, and probably would be for many similar plants. Consistently, through-plant removal of phosphorus was more effective than by equivalent dosing of Fe(III) to raw influent or to primary effluent, but only marginally more effective than equivalent dosing of Fe(II) to primary effluent (Tables VI-VIII).

Fe(II) vs. Fe(III): To Raw vs. to Primary Effluent--The lesser dosage efficiency of Fe(III) was attributed principally to the very slow mix with raw influent and to an inadequate quick mix when injection was to the primary effluent. Hydrolysis of Fe(III) was extensive before homogeneity was attained, thereby, even when dosage was proportional to influent phosphorus load, resulting in formation of hydrolytic products low in phosphorus content. Whereas for Fe(II), even with slow mix, homogeneity was insured before appreciable oxidation, hydrolysis, phosphate uptake, and flocculation had occurred. These proceeded in close sequence in the short length aeration tanks, wherein high rate of sludge return and the near complete mix from turbulent aeration had leveled out fluctuations of phosphorus concentration of the plant flow. Thus, the need for proportional feeding was reduced. Injection of Fe(II) to raw influent at two-level diurnal dosage rate showed only slightly increased dosage efficiency over single-level rates (Tables V and VIII, Ferrous to Raw Influent). A further advantage of using

ferrous iron is that it can be supplied at lower cost. Additional advantages of dosing to raw influent, Fe(II) or Fe(III), include: first, sulfide is tied up in non-volatile form, reducing odor nuisance; second, insolubilization of phosphorus in any by-pass portion is insured; and third, daily phosphorus loads in the total flow can be estimated more closely than the loads in the through-plant portion of flow.

Reactions through Primaries--Injection of Fe(II) to the raw influent effected essentially no removal of phosphorus across primaries, and very little, if any, increased removal of solids and COD (Table VII, Columns 8-13. Note: the indicated negative removal of solids was due to delayed precipitation in samples between time of collection and assay). There was immediate evidence of formation of colloidal to visible precipitate, increasing through primaries, but at average to high flow, not to a settleable form or quantity for appreciable removal of phosphorus. The high alkalinity of the raw influent, 400-500 mg/l at dry weather flow, held pH within a range of 7.0-7.5, evidently non-optimal for precipitation and flocculation of ferrous phosphate. At diurnal periods of very low flow, and at times of oxygen-carrying water from infiltration, there was some oxidation to Fe(III) with accompanying and somewhat proportional precipitation and flocculation, but not enough settling to result in major removal of phosphorus.

In contrast to injecting Fe(II) to raw influent, equivalent dosing of Fe(III) resulted in considerably more settling of iron, and some more of phosphorus, across primaries, but less through-plant removal of phosphorus. At diurnal periods of low flow and concurrent low influent phosphorus concentration, precipitation and settling of iron and phosphorus approached completion. Thus, at single-level dosing rate, there was settling and re-

moval of iron carrying much less than its stoichiometric share of phosphorus. This loss of excess iron to primary solids was sufficient to account for much of the lower through-plant removal when dosing of Fe(III) was to the raw influent.

Wasting of high ferri-phosphate aeration solids to the primaries had little effect on primary processes other than to thicken solids to a uniform consistency for convenient scheduling of pumping of sludge to the digester. The mass of the waste solids settled rapidly, with marginally measurable reduction in soluble phosphorus. But partial deflocculation resulted in carry-through of some of the high-phosphorus solids, often registering a net increase of phosphorus through primaries.

Fe(II) to Raw Influent: Parameters near Optimal for Removal of Phosphorus through Aeration--Bringing of almost the total iron dosage, still as Fe(II), homogeneously mixed in primary effluent, then in the return sludge, was favorable for high uptake of phosphorus, even at single-level dosage rates. The near complete mix in the tanks dispersed the dosage before the sequential oxidation, hydrolysis, phosphorus uptake and flocculation were complete. Also, the complete mix plus high volume sludge return leveled out variations in phosphorus concentration, affording approach to proportional feeding. Thus, each newly formed ferric particulate, capable of absorbing phosphorus, was afforded maximum opportunity of attaining its stoichiometric requirement from available phosphate ions--whether by ion combination (12), by physical adsorption (30), or by complexation of hydrolytic products (35). The high rate of sludge return and maintaining aeration solids at high level (2000-4000 mg/l), extended the contact opportunity by the mass of high iron solids, through a net retention of 4-8 days. It was not possible to demonstrate precisely the extent of this con-

tinued uptake. But the around-the-clock uniformly low level effluent phosphorus was evidence that continued absorption of phosphorus was appreciable (Figures 10-12).

The oxidation of Fe(II) to Fe(III) imposed no burden on air supply (only 1 lb of oxygen for 7 lbs of iron). It was possible to hold DO in aeration effluent near 1 mg/l, a level favorable for removal of COD and suspended solids, also evidently favorable for precipitation and flocculation of phosphate solids (Table VII, Columns 8-13; Aeration Solids, TSS and COD).

There was no way for discerning how much of the phosphorus uptake was biological precipitation. It was assumed that it was no greater than the 10-15% in demonstrations with no added cations immediately preceeding and following periods with use of iron (Tables II and III). But the augmentative doses of iron for 80-90% removal of phosphorus were no greater than would have been required to hold biologically released phosphorus with the digester solids.

Flocculation and sedimentation of aeration solids were highly effective as evidenced by the low SVI values, low effluent solids and COD, and by the observed sparkling clarity of the effluent (Tables V-VII; Figure 9). Even the high degree of denitrification was not inhibitory to the removal of the high ferri-phosphate solids (Table V-VII, Nitrogen and TSS). The effective flocculation and the heavy solids minimized the floating and carry-through by evolving nitrogen.

The aeration effluent pH range of 7.3-7.6 evidently was favorable to precipitation and flocculation of ferri-phosphate solids. The range was well above 5.3, pointed to by Stumm (16, 25) as the pH of minimum solubility of

phosphorus in equilibrium with ferric phosphate; above 6.0-7.0 observed by Tenney, et.al.,(40) as the range for rapid formation of Fe(III) hydrolytic products favorable for flocculation and conditioning of activated sludge: and well below 8.8, demonstrated by Wuhrman (24) as favorable for removal of phosphorus from secondary effluents by Fe(III), using lime for pH adjustment. But within the experiential range of 7.3-7.6, 80-90% removal and disposal of phosphorus was effected, by mol doses of 1.3/1 to 1.6/1, Fe(II)/P, injected into the raw influent at around-the-clock single level dosage rates.

Effective Doses: for 80-90% Removal, 1.3/1 to 1.6/1, Fe(II)/P

Demonstration results indicated that a certain per cent removal of the influent phosphorus load could be expected from a given mol dose of ferrous iron, somewhat independent of the influent phosphorus concentration, and through considerable variations in levels of other parameters. Precise demonstration of this, on a day to day basis, was not possible, since daily and diurnal variations in flow and phosphorus load precluded prediction and application of exact mol doses. Also, the daily dose effects, due to the 8- to 12-hour flow-through period, were not reflected in the analyses of 24-hour composite samples. But averages of daily values for periods of at least three days, when maxima and minima were not extremely variant from the means of the periods, pointed significantly to the effectiveness of specific mol dose. The selection of the demonstration periods of Tables VI-VIII was on this basis. It is believed that results were close to what would have been, had the average mol dose of a respective period been applied each day of the period.

As a test of correlation of doses of ferrous iron with phoshorus

removal, 3-day moving averages of applied mol doses (AMR, Fe/P) were plotted against respective 3-day moving averages of percent removal of phosphorus, for 75 days of dosing of Fe(II) (Figure 13a). These included one-level and two-level dosing rates to raw influent, but only one-level rates to primary effluent. Days were not included when influent phosphorus dropped below 3mg/l, ie, at times of extremely high infiltration when flow measurement and proportional sampling became non-reliable (Table V). Also May 3, was excluded because it was non-representative of controllable operation. Non-attention permitted through-plant flow to rise to 1.5-1.6 MGD for 3 hours, about .3 MGD higher than could be tolerated without excessive loss of solids to effluent. (Table V and Figure 9: note effluent solids, TSS=141 mg/l; effluent P=8.3mg/l; and effluent COD=108mg/l).

Effects of mol doses, AMR, were not linear, but closely so, through the range of 1.0/1 to 1.6/1, Fe/P. The curve of linear best fit presented in Figure 13a is for the equation, y=50.55+22.32X; correlation coeffecient, +0.6975, significant at 1% level.

Limited observations at mol doses above 1.5/1, Fe/P, indicated decreasing efficiency with increasing doses. This appreared to be a limitation of insolubility rather than of flocculation and settling. Thus, for removal of as much as 95% of phosphorus load, adjustment of pH toward a level of lesser solubility might be required, ie, toward 5.3, the pH of minimum solubility of phosphorus in equilibrium with solid ferric phosphate (16, 25). Then, if solid separation is not adequate for reducing effluent phosphorus to a desired low level, eg, less than 0.5mg/l, the use of a coagulant aid and/or effluent filtration would be indicated.

Again, by inspection of over-all results, plus consideration of the above test of correlation of AMR values with % removal, a significant observation was that mol doses of ferrous iron of 1.3/1 to 1.6/1, somewhat independent of influent phosphorus consentration, effected 80 to 90% removal of the influent phosphorus load. This was sharply true for AMR values of 1.4/1 to 1.6/1, within a phosphorus range 4.9-9.4mg/1.

Of the 73, 3-day moving averages of AMR values, 21 were in the range of 1.40/1 to 1.60/1; average 1.50/1. The range of the respective values for % removal of phosphorus was 80.3-90.3; average, 85%. The influent phosphorus range was 4.9-9.4mg/1; average, 7.3mg/1; median, 7.3mg/1. Therefore, for an influent phosphorus range of 5-10mg/1, 85% removal of the phosphorus load could be expected when a mol dose of 1.5/1, Fe(II)/P was applied.

Opportunity was not afforded for using ferrous iron at times of low dry weather flow when influent phosphorus was as high as 12-14mg/1. Comparison of results (Table VII, Columns 8-13; Table VIII, Ferrous to Raw Influent) at lower influent phosphorus, 4.5-6.5mg/1, with results at levels of 7.5-9.5mg/1, indicate that only slightly lower dosage efficiency might be expected at still higher influent phosphorus levels.

Sludge Production, Digestion and Dewatering

Increased solids production by use of iron in the activated sludge process was close to the estimated production of hydrolytic and phospho-products (Table XIII). Volume production was about 10% less than with no cationic treatment. There was no significant indication of change in production of organic solids. Digestion retention time was reduced by about 25%, but digestion was rapid and effective.

Compaction of solids in digestion was about the same as for digestion of normal primary plus activated sludge, ie, to 5-6% dry weight solids. Draining, cracking and drying of the digested sludge on the drain beds, were fully as rapid and effective as for digested solids from primary plus activated sludge. The dry solids were appreciably more friable.

Digester and drain bed capacity was about 70% over conventional design. This was evidently adequate for digesting and dewatering of the high phosphate high iron solids.

Chemical and Overall Costs

On the basis of 85% removal of a 10mg/l phosphorus load in 1 MG(3790 c m) of wastewater, by a 1.5/1 mol dose of iron, Fe(II)/P, and $0.10/lb for iron the chemical cost was $.32/lb of phosphorus removed; $22.50/MGD; $225.00/day for a 10 MGD plant. Chemical costs constitute almost the total costs, therefore from region to region the costs for iron treatment would be almost directly proportional to delivered cost of iron.

For the design, procurement and installation at a local (Houston area) 1 MGD plant, of a 4000 gallon (15.1 cu m) rubber lined steel tank, a double-head chemical metering pump, plus necessary piping the cost was $7000. For a 20-year amortization, plus maximum expected repair and maintenance the additional costs would not exceed $2.50/MGD, thereby totaling about $25/MG at a 1 MGD plant for chemical and equipment costs.

"Iron-handling" entails additional through-plant housekeeping and maintenance but the over-all "ironing-out" of control of treatment process compensates for the additional operational costs, including the disposal of an additional 20-30% digested solids.

REMOVAL AND DISPOSAL OF PHOSPHORUS
BY USE OF ALUMINUM CHLORIDE

To Raw Influent

Demonstrations were at only three incremental dose levels, with injection to the raw influent: 1.25/1 and 2.04/1, Al/P at single-level diurnal rates and 1.79/1 at two-level rates; effecting 68%, 69% and 74% removal of phosphorus; and 70%, 71% and 77% insolubilization, respectively (Table XII, also X and XI).

It was readily evident that more rapid mix and more rigidly proportional doseage would be required for greater dosage efficiency. Hydrolysis was considerable before homogeneity was attained. Flocculation was in evidence in the primary influent. At diurnal low flow, precipitation of aluminum and phosphate was near complete across primaries, and flocculation and sedimentation, extensive. Thus, during the 2- to 6- hour low flow low phosphorus periods most of the phosphorus was removed with primary solids, but there was excessive loss of hydrolyzed aluminum, carrying less than its stoichiometric capacity of phosphorus. During the longer diurnal periods of higher flow, controlled at near uniform rate, almost the total of the dose of aluminum was carried through primaries, with precipitation and flocculation still in progress.

Reactions were complete and flocculation effective in aeration (Table X: note effluent total and soluble and TSS values). But total removal of phosphorus did not reach even an 80% level, attributable to loss in primaries of hydrolyed aluminum low in phosphorus content, which in turn was attributable to slow mix and non-proportional dosing.

Aluminum to Primary Effluent

Dosage efficiency was better with injection into primary effluent. But dosing at 2-level diurnal rates was only slightly more efficient

than at single-level rates. The three incremental doses at 2-level rates, 1.65/1, 2.02/1 and 2.41/1, Al/P, effected 81%, 82% and 80% removal of phosphorus, and 84%, 87% and 92% insolubilization, respectively (Tables X-XII, Sept. 9-23). Two incremental doses, at single-level rates, 2.20/1 and 2.41/1, removed 82% and 80% of phosphorus, and insolubilized 92% and 92% (Tables X-XII; Oct. 2-6 and Sept. 24-Oct. 1). Thus, it was noted that an upper limit of about 80% removal was reached at doses of 1.6 /1, 1.8/1, Al/P, and an upper limit of about 90% insolubilization, at doses of 2.0/1, to 2.2/1.

Barth and Ettinger (34) attained 95% removal of 12mg/l phosphorus by a 1/1 mol dose of sodium aluminate, added to aeration liquor, with a resultant pH level of 7.2-7.5. This high dosage efficiency was attributable to at least 40% of the uptake being biological precipitation, to rigidly proportional dosing, and to the aeration pH level being near optimum. Eberhardt and Nesbitt (33) removed 93% of 13.8mg/l of phosphorus, by a 1.9/1 mol dose of aluminum sulfate, added to aeration liquor with resultant pH of 5.5; near 5.0, the level pointed to by Stumm (25) for minimum solubility of aluminum phosphate. Wukasch (29) increased phosphorus removal by Fe(II) through primaries, by use of polyelectrolyte coagulant aid. Therefore, for increased dosage efficiency for Al(III) at the Texas City plant No. 2, the following were indicated: greater biological precipitation, more rigid proportional dosing, raising of pH for improved flocculation, lowering of pH for reduced solubility of aluminum phosphate and improved flocculation, filtering of effluent for removal of alumina-phosphate solids, and/or better flocculation and settling. Opportunity was afforded only for the last.

There was no evidence that biological uptake of phosphorus could have been increased above the 10-15% removal experienced immediately before and after the demonstration of the use of aluminum.

The mix of the dosage in the confluent stream of primary effluent and return sludge was not sufficiently rapid to prevent considerable hydrolysis of aluminum before homogeneity was attained; in effect, reducing proportional dosing, and thereby indicating need for quicker mix. The slightly greater efficiency of 2-level diurnal feeding rate over single level rates, indicated that appreciably greater dosage efficiency would have been experienced with rigidly proportional dosing.

Insolubilization of phosphorus increased with increasing doses above about 1.7/1, Al/P, but poorer flocculation and settling prevented increased removal above the 80-82% level (Table X-XII; note effluent total and soluble P and TSS; also EMR values). The lower aeration pH, 7.0-7.3 at the higher doses as compared to 7.2-7.5 at lower doses, may have been sufficient to have accounted for the poorer flocculation and settling. Laboratory filtration tests indicated that sand filtration would reduce effluent suspended solids and phosphorus sufficiently to augment phosphorus removal to 90% at mol doses of 2/1, Al/P.

Bench-scale tests plus the 4-day plant-scale demonstration of dosing a polyelectrolyte to aeration effluent indicated that removal of phosphorus could be augmented to 90% from a mol dose of aluminum as low as 2.2/1 (Tables X-XII, Oct. 7-10). The effective dose of coagulant aid was 1mg/l, based on plant influent flow, or about ½mg/l based aeration effluent flow rate.

Sludge Production, Digestion and Dewatering

At the mol dose of 1.65/1, Al/P for 81% removal of phosphorus, the daily volume of sludge pumped to the digester was about 20% greater than for camparable operation with no cations added to primary or aeration processes. The total weight of solids was about 50% greater (Table XIII). During the 57 days of operation with added aluminum, the average mol dose was about 2.2/1, approximately the dose that would have effected 90% removal with the aid of a polyelectrolyte coagulant. The weight of sludge at this average 2.2/1 mol dose was proportionately greater than at the 1.65/1 mol dose, but the volume production was only slightly greater.

Digestion proceeded rapidly in the digester but the residual sludge failed to compact to more than about 2.5% solids, dry weight basis (Figure 18). Therefore, retention time was reduced by about 50%, entailing the drawing of "green" sludge. Digestion proceeded on the drying beds, with no odor nuisance, and with completion in about 15 days. The on-bed digestion with gas evolution left a final sludge mass that drained, cracked and dried effectively, and was readily removable and quite friable

The digester and drain beds were about 70% over-size of conventional design capacity. It is estimated that an additional 100% over-size would be required for digesting and dewatering such a high alumina-phosphate sludge.

Chemical and Processing Cost

The market price of the aluminum chloride solution used was $0.075/lb of Al, FOB Texas City, 0.10/lb delivered to most points in the area. For 80% removal of 10mg/1 phosphorus in 1MG of waste water, the chemical cost would be $.85 /lb of phosphorus removed;

$12.30/MGD. The costs for chemical storage and feeding facilities, including procurement, installation, repair and amortization would be of the same order as for the use of Fe(II) or Fe(III), is about $2.50 for a 1 MGD operation. The total costs for chemicals plus storage and feeding facilities would be about $15/day for a 1 MGD plant.

For 90% removal of 10mg/l phosphorus load by a 2.2/1 mol dose of aluminum plus 1mg/l of a coagulant aid, the chemical costs plus chemical storage and dosing facilities would be in the order of $38/day for 1 MGD operation.

The requirements for additional digesting and solids dewatering facilities are not closely enough known for determination of these additional costs.

SUMMARY AND CONCLUSIONS

In a 0.7 MGD activated sludge plant, demonstration studies were made of effectiveness and feasibility of biological, chemical and physical processes for removal and disposal of phosphorus.

BIOLOGICALLY RELEASED PHOSPHORUS REPRECIPITATED FROM DIGESTER LIQUOR

To recover, and to prevent its recycle to plant processes, released phosphorus in digester liquor was chemically precipitated, dewatered on sand beds and spread on soil deficient in phosphorus.

Concurrent with this practice, 25-60% biological uptake of phosphorus by activated sludge was experienced, producing waste aeration solids containing 2.5 to 4.5% phosphorus. Anaerobic digestion of these solids released 100-260 mg/l of phosphorus to digester liquor. At these levels, precipitation and recovery by use of lime, Fe(III) or Al(III) was operationally and economically feasible.

For levels above about 150 mg/l and based on comparative volumes of sludge produced, dewaterability of the solids, and chemical costs, the precipitants of choice, in order, were: hydrated lime, Fe (III) and Al(III).

In a 12-day period phosphorus content of waste solids was 2.0-3.5% Through-plant removal of phosphorus was 41%. Soluble phosphorus digester liquor reached 249mg/l. Lime dosage of the liquor to pH 9.0, requiring 7.3 lbs of lime per lb of phosphorus precipitated, reduced phosphorus content of the liquor to 7mg/l, at a chemical cost of $0.12/lb of phosphorus removed. Thus, when biological uptake by aeration solids was 41% of 10mg/l phosphorus, the indicated chemical cost was $4.10/MGD.

BIOLOGICAL REMOVAL OF PHOSPHORUS
BY ACTIVATED SLUDGE

As a premise for effective removal of phosphorus by activated sludge it was recognized that phosphorus content of aeration solids would have to be well above 1.5%, a level required for cell reproduction, and that net building of cell solids would have to be high, eg, for 90% removal of a 10mg/l phosphorus load, 5% phosphorus content and net solids building of 180mg/l.

Through a first series of observations, totalling 158 days, phosphorus content of aeration solids regressed from a high of 5% to a low of 1.6%, with a periodic recovery to 3-3.5%. Net solids building average less than 100mg/l, but through several 3-day periods reached 130-170mg/l. Phosphorus removal regressed from about 50% to a 3-day average of about 15%, but in two 3-day periods averaged 60-70%, also in one 3-day period fell to zero.

In a second series of observations, totalling 73 days, phosphorus content of cell solids never exceeded 1.8%; net solids building averaged about 100mg/l, with peak 3-day averages of 140-150mg/l; and average phosphorus removal was 13%, with 3-day averages ranging from -4% to 17%.

In the first series of observations (158 days), operation control and lack of control, were characterized as follows. With the exception of one month there was moderate to heavy rainfall, with proportional infiltration, extended through the period. Primary clarifiers were out of service through the first 106 days. Through-plant flow and loadings experimentally, then, unavoidably, were limited to 70-90% of total. Air application and solids management were for effective removal of COD and suspended solids, for minimum anoxic release of phos-

phorus, enrichment of solids, and except for the last 30 days, without excessive aerobic digestion and nitrification. In addition to regular diurnal and day-to-day variations in flow and loadings, there were irregular extremes from inflitration. As compared with "plug flow" the flow-through aeration pattern was near complete mix.

In the second series of observations, (73 days) low dry weather flow prevailed. Total flow and loading were accepted. At the low dry weather flow, diurnal variations in flow and COD loadings were sharper. In proportion to flow, a higher inventory of aeration solids was maintained. Air application was held at maximum capacity. Aerobic digestion of solids, and nitrification, were extensive. Complete mix in aeration was intensified by the lower flow, by a higher rate of sludge return, and by the more turbulent mix of high rate air application.

The inability to maintain high phosphorus enrichment of aeration solids and high net building of solids, and thereby, high removal of phosphorus, was attributed to complete mix aeration, to frequent and variations in COD and phosphorus loadings, and to extensive aerobic digestion of cell solids. Before log growth of cells and subtrate utilization could be brought to near completion, and aeration extended into nutrient imbalance of declining growth_conditions favorable to biological enrichment of cell solids_ a fresh supply of nutrients, continually and in slugs, entered the complete mix system. The new supply not only reestablished log growth cell building, but also promoted release of phosphorus enrichment from old cells. Then, the extended intensive aeration of a high inventory of cell solids, promoted digestive release of phosphorus and reduced the population of cells capable of phosphorus enrichment.

It was therefore concluded that in small activated sludge plants such as Texas City #2, with complete mix aeration and wide and sharp variations in COD and phosphorus loadings, high level phosphorus removal cannot be maintained.

PHOSPHORUS AND MAGNESIUM CO-ENRICHMENT OF AERATION SOLIDS

Assay of phosphorus, magnesium and calcium content of aeration solids was made through extended periods when there was phosphorus enrichment; also, when limited doses of lime produced increased calcium content of the activated sludge but no increased phosphorus or magnesium content. It was observed that for each mol of phosphorus enrichment above the 1.5% level, there was uptake of about 1/3 mol of magnesium, but no increased uptake of calcium. The results of these observations are considered as evidence of biological phosphorus and magnesium co-enrichment of activated sludge solids.

FERRIC AND FERROUS IRON TO PRIMARY EFFLUENT AND TO RAW INFLUENT

Demonstration objectives were to determine mol dose requirements, Fe/P, of Fe (III) and Fe(II), to primary effluent and to raw influent, for attaining 80-90% removal of phosphorus. Injections of Fe(III) to primary effluent was for 38 days, and to raw influent for 33 days; of Fe(II) to primary effluent for 33 days, and to raw influent for 49 days. Dosing, diurnally, was at single-level rates, except at two-level rates for 6 days of Fe(II) to primary effluent, and 10 days to raw influent.

Dosage efficiency for Fe(II) was better than for Fe(III), into primary effluent or into raw influent. Dosing of Fe(II) to raw influent was more efficient than to primary effluent. Dosing of Fe(II) to raw influent two-level diurnal rates was slightly more efficient than by single-level rates. Injection into the total flow of raw influent insured insolubilization of phosphorus in by-pass flow at times of heavy infiltration; tied up

sulfides into non-volatile form; and, along with feeding at around-the-clock uniform rates, facilitated estimating and applying required daily doses.

Therefore, the demonstrated effective and most feasible process was by dosing Fe(II) to raw influent at constant level diurnal rates. Mol doses of 1.5/1, Fe/P, dependably removed 85% of the influent phosphorus load. Through 44 days of such operation with daily phosphorus at 4 to 10mg/1, averaging 7mg/1, doses of 1.3/1 to 1.6/1, averaging 1.5/1, removed 83 to 88%, averaging 86%, reducing effluent phosphorus to 1.0mg/1. Effluent suspended solids averaged 7mg/1, for across-plant reduction of 95%; effluent COD, 29mg/1, for 85% reduction.

Influent mix of dosage was slow, but homogeneity was attained before there was appreciable hydrolysis or phosphate precipitation of Fe(II), or oxidation to Fe(III) and hydrolytic precipitation of ferric phosphate. Removal across primaries by precipitation of ferrous or ferric phosphate, was small. Most of the dosage reached the aeration units as Fe(II), homogeneously mixed with return sludge, for sequential but rapid oxidation to Fe(III), hydrolytic precipitation of ferric phosphate, and effective flocculation with the activated sludge.

Increased sludge production was demonstrably close to the estimated amount from ferri-hydrolytic phosphate precipitation. The combined volume of waste and primary sludge was 10-15% less than when no cations were added. The high ferri-phosphate sludge digested effectively in the 70% over-capacity digester. The iron was reduced to the ferrous state, but over 95% of the phosphorus remained with the ferro-sludge. Drainbed draining, cracking, drying and removing of the digested solids were fully as rapid and effective as for digested solids from conventional primary plus activated sludge.

For 85% removal of phosphorus by a 1.5/1 mol dose of Fe(II), at $0.10/lb for iron, the chemical cost was $0.32/lb of phosphorus removed. For influent phosphorus at 10mg/l this would amount to $22.50/day for a 1 MGD operation. For a 1 MGD plant in the Texas City-Houston area, the estimated additional costs for the chemical storage and dosing facilities, including design and installation plus 20-year maintenance and debt amortization, would be $2.50/day.

ALUMINUM CHLORIDE TO RAW INFLUENT
AND TO PRIMARY EFFLUENT

Incremental doses of aluminum chloride of 1.3/1 and 2.0/1 Al/P, to raw influent at single level diurnal rates, effected 68% and 69% removal of phosphorus. A dosage of 1.8/1, at two-level rates, effected 74% removal. The high rate of hydrolytic precipitation during slow mix, and continuing precipitation at non-proportional dosing, particularly during low flow, resulted in appreciable loss of the dosage, carrying less than its stoichiometric capacity of phosphate. From these limited observations it was concluded that very rapid mix at rigidly proportional dosing would be required for efficient use of aluminum, when injection was into the raw influent.

Dosage efficiency was better with injection into primary effluent, with slightly better efficiency at two-level than at single level rates. But an upper limit of about 80% removal was reached at doses of 1.6/1 to 1.8/1, Al/P, and an upper limit of about 90% insolubilization of the phosphorus load, at doses of 2.0/1 to 2.2/1.

For more efficient use of aluminum chloride at the Texas City Plant No. 2, the following were indicated: more rapid mix of the dosage; more rigidly proportional feeding; raising of pH for improved flocculation; lowering of pH toward the level of least solubility of

aluminum phosphate; filtration of the plant effluent; and/or using a coagulant aid for better flocculation and settling. Only the last process was verified.

Increased solids production was close to the estimated amount from the alumina-hydrolytic phosphate precipitation. The combined volume of waste and primary sludge was about 20% greater than when no cations were added.

Sludge digestion was rapid but compaction was poor, thereby limiting digestion time. Sludge drawings were "green," but on-bed digestion was complete in about 15 days, without odor nuisance. Final draining, cracking and drying were effective to a readily removeable and friable cake. It is estimated that the digestion and/or drain bed facilities would have to be increased by about 100% (170% over conventional design capacity), for effective digestion and drying of the high alumina-phosphate sludge.

At $0.10/lb for contained aluminum in the aluminum chloride, the estimated chemical cost for 80% removal of 10mg/l phosphorus would be about $10/day for 1 MGD operation. Adding a $2.5/day cost for procurring and maintaining chemical storage and feeding facilities, the costs for chemical precipitation of phosphorus at an 80% removal level by use of this low cost aluminum chloride would be about $12.50/MGD. Sufficient experience was not obtained for estimating the cost of providing and operating the additional digester and drain bed facilities.

For 90% removal of 10mg/l phosphorus by a 2.2/1 mol dose Al/P of aluminum chloride, plus 1mg/l of a polyelectrolyte coagulant aid, the cost for chemicals plus costs for procurement, maintenance and debt amortization for storage and feeding facilities, would amount to about $38/day for a 1 MGD operation.

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Mr. E. F. Barth was the Project Officer for the Water Quality Office, Environmental Protection Agency.

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TABLE I. - REMOVAL OF PHOSPHORUS BY ACTIVATED SLUDGE WITH NO ADDED CATIONS WHEN THERE WAS EVIDENCE OF BIOLOGICAL ENRICHMENT OF AERATION SOLIDS

Daily Average Operation and Index Parameters
August 1 - September 10, 1968*

Date 1968	Total Flow MGD	Plant Flow MGD	Total P mg/l Raw Infl	Total P mg/l Final Effl	%P in Aer Solids	% Rmvl of P	Mg/l Aer Solids	SVI	COD loading mg/l	COD loading lbs/day	COD/ MLS**	DO in Aer Effl	Kjeldahl-N mg/l Raw Infl	Kjeldahl-N mg/l Final Effl	NO_3-N Final Effl mg/l	TSS in Final Effl Mg/l	COD in Final Effl Mg/l
Aug																	
1	.550	.460	10.4	8.2	2.1	21	1785	521	266	1018	.32	.7	-	-	-	11	51
2	.550	.433	10.3	7.7	2.2	25	1780	520	327	815	.25	.5	30	21	.5	12	54
3	.545	.418	10.0	6.4	2.0	36	1990	470	351	1222	.34	.6	30	19	.6	19	57
4	.515	.417	9.7	11.8	2.1	39	1750	520	312	1086	.34	.7	29	18	.5	21	53
5	.515	.415	10.8	7.2	2.3	33	1835	500	338	1165	.35	.6	26	16	.2	8	52
6	.625	.415	9.5	7.2	2.5	24	1825	500	322	1114	.34	.6	28	12	.2	15	58
7	.550	.402	8.7	5.9	2.7	32	1795	520	299	1004	.31	.6	26	12	.4	18	45
8	.520	.419	10.6	7.3	2.8	31	1795	510	323	1129	.35	.4	26	12	.5	4	51
9	.490	.415	12.0	8.7	2.8	28	1805	490	287	994	.31	.3	26	15	.5	5	34
Av (1-9)	.540	.421	10.2	7.8	2.4	30	1818	506	314	1061	.32	.6	28	16	.4	13	51
10	.495	.398	12.0	7.4	3.5	38	1590	533	251	834	.29	.6	32	10	.8	9	34
11	.455	.405	10.4	6.2	3.5	40	1575	514	265	896	.32	.5	29	11	.5	10	33
12	.535	.436	11.7	7.4	3.4	37	1615	508	323	984	.34	.9	38	13	.4	10	38
13	.490	.419	11.9	7.9	3.2	34	1680	482	451	1576	.52	.9	30	18	.4	10	40
14	.475	.385	12.2	5.7	3.1	53	1775	428	262	842	.26	.9	31	12	.4	12	52
15	.475	.355	11.3	5.5	3.8	51	1540	416	244	724	.26	.9	29	11	.4	8	20
16	.490	.390	12.0	5.6	4.1	53	1476	501	320	1040	.39	1.0	-	-	.2	11	42
17	.465	.376	12.2	6.3	3.4	48	1630	460	330	1036	.35	.7	33	12	.2	7	44
18	.490	.394	10.3	6.7	4.0	35	1490	510	302	995	.37	.7	32	14	-	35	47
19	.475	.375	11.5	6.8	3.9	41	1570	522	320	1002	.35	.6	32	12	.4	17	35
20	.475	.385	12.0	8.2	3.5	32	1618	500	338	1082	.37	.5	24	10	.5	14	32
21	.475	.380	11.0	6.7	3.4	39	1676	500	360	1144	.34	.5	26	12	.9	8	25
22	.475	.375	12.0	6.4	3.3	47	1696	460	362	1021	.33	.5	28	12	.5	10	36
23	.750	.369	7.6	5.3	3.3	30	1842	418	381	1171	.35	1.1	22	2	1.4	14	39
24	.600	.371	8.2	3.1	2.9	62	1834	414	272	840	.25	1.3	23	8	1.8	5	37
Av (10-24)	.508	.388	11.1	6.3	3.5	43	1640	478	319	1012	.34	.8	29	11	.6	12	37
25	.600	.357	8.3	7.9	2.4	5	1972	380	260	775	.22	1.0	26	8	1.7	5	43
26	.530	.378	10.1	6.2	3.0	39	1922	380	260	820	.24	1.0	24	4	1.6	16	20
27	.550	.405	10.4	7.7	2.7	26	1910	372	289	977	.28	1.0	25	4	1.2	6	22
28	.540	.406	10.4	7.4	2.8	29	1850	378	265	885	.27	1.1	28	5	1.2	21	42
29	.550	.403	10.8	7.2	3.0	33	1772	305	264	890	.28	1.1	28	5	1.3	7	28
30	.510	.420	9.3	6.9	3.0	26	1626	258	-	-	-	1.2	-	-	-	8	-
31	.465	.390	11.0	6.7	3.0	39	1514	257	284	955	.35	1.2	30	5	2.4	4	34
Sept.																	
1	.560	.360	9.5	7.2	2.8	24	1450	228	280	830	.32	1.0	31	5	3.6	16	34
2	.575	.375	10.1	6.2	2.9	39	1400	193	270	844	.33	1.0	32	5	4.0	4	48
3	.730	.425	9.0	6.9	2.7	23	1332	225	287	1017	.42	1.0	26	7	-	8	34
Av (25-3)	.558	.392	9.9	7.0	2.8	28	1675	298	274	888	.30	1.1	28	5	2.1	10	34
4	1.809	.659	7.7	6.4	2.4	17	1420	162	236	1298	.50	1.1	26	7	1.9	5	37
5	1.797	1.047	3.6	3.2	1.8	11	1450	118	164	1431	.54	2.2	10	3	2.2	6	40
6	1.253	.973	5.3	3.2	1.7	40	1350	96	73	600	.25	1.2	13	3	2.3	6	25
7	.818	.768	9.3	6.9	1.5	26	1316	84	150	961	.40	1.0	20	10	.8	6	21
8	.641	.641	7.9	7.4	1.5	6	1294	85	145	776	.33	.5	20	17	1.1	14	34
9	.708	.708	5.7	5.3	1.9	7	1198	92	194	1146	.53	.6	21	15	.6	14	21
10	.577	.577	9.0	5.5	2.1	39	1202	92	217	1046	.48	.9	22	15	.9	10	48
Av (4-10)	.943	.768	6.9	5.4	1.8	21	1319	105	169	1037	.43	1.1	19	10	1.4	9	32

* There was no primary sedimentation during the period covered by this table.
**COD/MLS = COD load in pounds per day/pounds of mixed liquor solids under aeration.

TABLE II.—REMOVAL OF PHOSPHORUS BY ACTIVATED SLUDGE WITH NO ADDED CATIONS WHEN THERE WAS EVIDENCE OF BIOLOGICAL PHOSPHORUS ENRICHMENT OF AERATION SOLIDS

Operational and Index Parameters at Maximum, Minimum, and Mean Levels of Phosphorus Removal
June, 1968 - January, 1969

Period of	June 2-9			Aug 1 - Sept 3			Sept 4 - Oct 1			Oct 22 - Nov 26			Nov 29 - Dec 31			Jan 1 - 19		
Number of Days		8			34			28			35			33			19		
	Max **Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd
Number of days for average	3	3	8	3	3	34	3	3	27	3	3	36	3	3	33	3	3	19
Dates	June 3-5	June 6-8	June 2-9	Aug 14-16	Aug 25-27	Augl-Sept3	Sept 24-26	Sept 15-17	Sept4 Oct 1	Nov 24-26	Nov 18-20	Oct22-Nov26	Dec 2-4	Dec 11-13	Nov29-Dec31	Jan 17-19	Jan 2-4	Jan 1-19
							PARAMETER LEVELS											
1. Total flow to plant, MGD	.85	.64	.68	.68	.56	.53	.70	1.10	.85	.65	.70	.71	1.30	1.00	1.10	1.25	1.15	.98
2. Flow through plant, MGD	.74	.62	.66	.38	.38	.40	.58	.82	.66	.66	.65	.66	.98	.91	.89	.94	.85	.81
3. P in raw intl, mg/l	7.6	11.1	9.5	11.8	9.6	10.8	6.9	5.8	7.5	10.1	9.4	9.3	6.8	6.4	5.9	6.7	5.2	6.1
4. P in final effl, mg/l	4.0	8.1	5.8	5.6	7.3	6.9	3.7	4.7	4.9	5.4	8.0	6.6	3.0	6.4	5.0	3.5	5.1	5.2
5. % P in aeration solids (MLS)	4.2	4.6	4.4	3.7	2.7	3.0	3.4	2.3	2.5	2.8	1.8	2.5	2.1	2.3	2.1	1.6	2.1	1.9
6. % P removed	47	27	38	52	24	36	59	19	34	46	14	29	37	0	15	25	2	15
7. Aeration solids (MLS), mg/l	1414	1397	1425	1597	1934	1696	1788	1772	1539	1894	1680	1815	1361	1955	1665	1539	1640	1806
8. Sludge volume index (SVI)	361	378	371	448	377	432	123	70	89	373	119	189	117	473	306	159	204	211
9. COD loading, mg/l	152	159	158	275	270	305	278	174	198	247	207	243	119	134	141	106	139	150
10. COD loading lbs/day	944	818	875	865	856	1024	1352	1194	1130	1366	1139	1360	1118	1492	1243	832	920	1071
11. lbs COD/day/lbs MLS	.37	.32	.34	.30	.25	.37	.42	.37	.41	.40	.37	.41	.40	.33	.29	.30	.41	.33
12. COD/P ratio	20.	14.	17.	23.	38.	28.	31.	30.	26.	24.	22.	26.	25.	34.	24.	22.	25.	25.
13. DO in aeration effluent, mg/l	.6	-	-	1.1	.9	.8	.6	.7	.7	1.1	1.9	1.1	1.7	1.7	1.4	1.3	1.3	1.3
14. *Kjeldahl N in raw infl, mg/l	18.3	21.5	20.6	30.2	25.5	32.9	25.3	15.6	19.8	24.7	21.2	22.6	12.5	15.1	14.6	11.8	14.7	15.7
15. *Kjeldahl N in final effl, mg/l	9.8	-	-	12.0	5.1	11.6	14.6	12.8	12.6	6.8	8.4	7.2	2.0	3.8	4.5	1.8	3.0	2.6
16. Nitrate N in final effl, mg/l	-	1.1	-	.3	1.5	1.0	2.8	.7	2.1	.6	1.1	1.2	.7	.7	2.0	4.1	5.3	5.9
17. COD in final effl, mg/l	29.	-	30.	38.	28.	40.	37.	69.	54.	37.	55.	44.	20.	76.	48.	30.	63.	38.
18. Suspended solids, mg/l	-	-	-	10.	9.	11.	19.	31.	19.	8.	11.	12.	6.	67.	37.	6.	22.	20.

*Including ammonia

**Rmvd - Removed

TABLE III. — REMOVAL OF PHOSPHORUS BY ACTIVATED SLUDGE WITH NO ADDED CATIONS WHEN THERE WAS NO EVIDENCE OF BIOLOGICAL PHOSPHORUS ENRICHMENT OF AERATION SOLIDS

Operational and Index Parameters at Maximum, Minimum, and Mean Levels of Phosphorus Removal
June - November, 1969

Period of	June 15 - 30			July 1 - 14			July 20-28			Aug 8 - 20			Oct 18 - 29			Nov 6 - 14		
Number of Days		16			14			9			13			12			9		
Number of Days for Average	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd	Max Rmvd	Min Rmvd	Av Rmvd
	3	3	16	3	3	14	3	3	9	3	3	13	3	3	12	3	3	9
Dates	June 26-28	June 17-19	June 15-30	July 10-12	July 6-8	July 1-14	July 21-23	July 25-27	July 20-28	Aug 10-12	Aug 16-18	Aug 8-20	Oct 20-22	Oct 26-28	Oct 18-29	Nov 6-8	Nov 9-11	Nov 6-14
							PARAMETER LEVELS											
1. Total flow to plant, MGD	.63	.61	.59	.62	.57	.58	.51	.55	.52	.52	.53	.53	.47	.60	.44	.61	.47	.44
2. Flow through plant, MGD	.63	.61	.60	.47	.56	.51	.51	.55	.52	.52	.51	.53	.47	.60	.44	.45	.47	.46
3. P in raw infl, mg/l	12.2	10.3	11.7	11.4	11.3	11.4	12.0	11.9	12.1	14.3	12.3	13.1	14.5	14.0	14.3	14.7	14.5	14.5
4. P in final effl, mg/l	10.1	9.3	9.8	9.4	10.0	9.5	10.7	11.2	10.9	12.0	11.8	11.7	12.3	14.5	13.3	12.2	13.0	12.5
5. % P in aeration solids (MLS)	2.0*	3.5*	2.7*	1.6	1.6	1.6	1.4	1.4	1.4	1.0	1.5	1.0	3.0**	2.3**	3.2**	1.9	1.8	1.8
6. % of P removed	17	10	16	18	11	17	17	6	12	16	4	11	15	-4	7	17	10	14
7. Aeration solids (MLS), mg/l	1409	1700	1450	1434	1428	1607	1728	1696	1748	1544	1755	1452	1254	1132	1236	1307	1788	1432
8. Sludge volume index (SVI)	440	180	333	467	480	424	115	100	201	509	576	539	305	633	458	146	432	447
9. COD loading, mg/l	242	248	253	261	260	262	270	292	278	318	291	300	274	319	283	308	332	313
10. COD loading, lbs/day	1270	1255	1453	1056	1109	1125	1134	1353	1214	1391	1239	1330	1080	1079	1039	1150	1310	1212
11. lbs COD/day/lbs MLS	.50	.41	.56	.41	.45	.44	.37	.42	.39	.50	.51	.53	.45	.47	.47	.44	.41	.41
12. COD/P ratio	20.	24.	22.	23.	23.	23.	21.	24.	23.	26.	25.	26.	22.	22.	21.	25.	26.	25.
13. DO in aeration effluent, mg/l	1.2	.8	1.0	1.9	1.0	1.3	.9	.6	.7	1.1	1.2	1.1	.8	1.1	.9	1.1	.4	.7
14. Kjeldahl N in raw infl, mg/l	25.5	21.3	21.9	25.7	26.2	24.0	29.0	30.0	28.4	30.4	28.1	29.2	32.9	40.0	35.4	34.2	40.5	37.5
15. Kjeldahl N in final effl, mg/l	10.1	10.1	9.1	2.7	5.3	4.8	2.5	4.8	3.5	5.8	2.9	4.1	3.7	8.6	5.3	8.2	7.6	6.7
16. Nitrate N in final effl, mg/l	7.0	1.9	3.2	10.7	3.9	6.2	10.6	4.6	8.1	7.4	7.6	6.9	9.3	8.6	11.0	15.5	12.2	12.9
17. COD in final effl, mg/l	23.	42.	29.	30.	39.	38.	30.	38.	37.	41.	53.	48.	29.	82.	55.	58.	59.	53.
18. Suspend solids, final effl, mg/l	3.	12.	7.	5.	5.	7.	7.	6.	6.	7.	11.	8.	9.	66.	32.	10.	6.	8.

* Residual high iron-phosphorus solids from iron dosing through June 14

** Residual high aluminum-phosphorus solids from aluminum dosing through October 17

TABLE IV. — REMOVAL OF PHOSPHORUS FROM DIGESTER LIQUOR WITH HYDRATED LIME
Average Operating and Index Parameters for One Day Runs,
In ascending order of resultant, final, pH of treated liquor

Column Number	1	2	3	4	5	6	7	8	9	10	11
Date 1968	Nov 4	Nov 8	Sept 19	Oct 26	Sept 24	Sept 27	Sept 6	Aug 29	Oct 22	Oct 17	Aug 18
Gallons of liquor processed	15,600	20,350	14,130	24,180	9,600	12,000	18,080	13,490	29,600	4,200	12,780
Digester liquor analysis											
pH	-	6.7	6.6	6.7	6.8	6.6	6.8	6.8	6.7	-	7.0
Alkalinity as $CaCO_3$, mg/l	1500.	1510.	1340.	1595.	1400.	1470.	1030.	1010.	1634.	1600.	950.
Acidity as $CaCO_3$, mg/l	1000.	918.	780.	1000.	885.	885.	-	700.	1000.	1000.	-
Total phosphorus, mg/l	228.	214.	162.	234.	179.	249.	131.	131.	238.	234.	102.
COD	359.	447.	269.	435.	341.	324.	267.	194.	371.	327.	196.
Total nitrogen by Kjeldahl, mg/l	292.	282.	214.	298.	198.	218.	-	125.	266.	298.	150.
TSS	348.	356.	202.	388.	304.	216.	168.	120.	260.	184.	136.
Lime Dosage, mg/l	2000.	2300.	1500.	2400.	1700.	1775.	1725.	1950.	3000.	3230.	2200.
Mol ratio, lime/P (AMR)	3.7	4.5	3.9	4.3	4.0	3.0	5.5	6.3	5.3	5.8	9.1
Weight ratio lime/P	8.8	10.8	9.3	10.3	9.5	7.1	13.2	15.1	12.6	13.8	21.7
Reactor effluent (filtered samples)											
pH	8.3	8.5	8.6	8.8	8.8	9.0	9.1	9.4	9.4	10.2	10.4
Residual phosphorus, mg/l of P	26.8	10.5	11.4	8.2	5.3	4.2	2.8	2.0	4.7	5.5	.8
COD, mg/l of P	128.	91.	112.	124.	120.	112.	75.	101.	122.	111.	127.
Sand bed sedimentation and filtration											
pH of supernatant overflow	8.3	8.7	-	8.8	8.3	8.2	-	-	9.2	10.2	9.7
Phosphorus in recycle liquor mg/l of P	7.2	6.4	4.4	7.4	6.5	7.0	3.1	-	6.9	10.4	1.7
Removals & efficiencies, across reactor											
% of P insolubilized	88.	95.	95.	96.	97.	98.	98.	99.	98.	98.	99.
% of COD removed	64.	80.	58.	72.	65.	65.	72.	48.	67.	66.	35.
Removals & efficiencies, total process											
% of P removed	97.	97.	97.	97.	96.	97.	98.	-	98.	96.	98.
Effective mol ratio, EMRr, lime/P	3.8	4.7	4.0	4.4	4.2	3.1	5.6	-	5.4	6.0	9.3
Effective wt. ratio, EWRr, lime/P	9.1	11.6	9.5	10.6	9.9	7.3	13.5	-	12.9	14.2	22.1
Deposits											
Soft deposits of $Mg(NH_4)(PO_4) \cdot 6H_2O$	severe	severe	slight	severe	slight	severe	slight	slight	severe	severe	slight
Sludge production per lb of P processed											
Pounds of dry solids	16.4	17.5	14.5	24.1	20.2	15.3	21.8	24.7	25.8	23.4	-
Cu ft of sludge at 30% solids	.41	.49	.41	.67	.57	.43	.61	.69	.71	.65	-
Cu ft of sludge at 60% solids	.14	.16	.14	.23	.22	.15	.21	.23	.24	.22	-
Pounds wet sludge at 60% solids	25.	29.	24.	40.	39.	25.	36.	41.	43.	39.	-

TABLE V. – REMOVAL OF PHOSPHORUS WITH FERROUS SULFATE INJECTED TO RAW INFLUENT

Daily averages of operation and index parameters – May, 1969

Date May 1969	Flow–MGD Thru Plant	By-Pad	Mol Dose Fe/P	COD mg/l Raw	FE*	Total P–mg/l Raw	PI*	FE	FE+ Bps*	Sol P mg/l FE	FE+ Bps	Aeration Solids MLS*	SVI*	%P Dry	%Fe Dry	TSS mg/l FE	Kjldl N* Raw	FE mg/l	NO_3-N FE mg/l	% Removal P Thru Plant	Plant + Bps	% P to Solids Thru Plant	Plant + Bps
												TWO LEVEL DOSING – WASTING OF RETURN SLUDGE TO BOTH PRIMARIES											
1	0.78	0.00	1.65	201	24	7.3	7.5	0.6	0.6	0.6	0.6	2300	100	5.6	–	4	19.3	3.5	7.9	91.8	91.8	91.8	91.8
2	0.67	0.04	1.48	247	22	8.7	7.6	1.0	1.7	0.8	0.9	2200	111	5.5	12.0	6	21.5	5.8	6.1	88.4	80.5	90.8	89.7
3**	0.84	1.00	0.91	280	108**	5.6	4.6	8.3**	6.5	0.8	0.6	2050	112	5.6	–	14i**	19.5	6.8	8.1	-48.0	-16.0	85.8	89.3
4	1.15	0.91	1.15	129	39	3.5	5.2	0.7	2.0	0.4	0.6	2100	100	4.7	9.8	8	15.0	3.9	6.0	80.0	74.2	88.8	88.2
5	1.76	0.34	1.34	174	34	5.3	5.2	0.9	1.8	0.5	0.5	2000	100	5.3	–	7	18.8	7.4	3.6	82.8	65.8	90.7	90.7
6	0.93	0.20	1.67	120	34	5.4	5.2	0.6	1.4	0.3	0.4	2050	105	5.0	11.8	6	16.8	4.0	2.7	88.8	77.0	94.6	83.6
7	0.82	0.10	1.92	148	45	5.3	5.1	0.6	1.0	0.4	0.4	2035	95	5.0	–	6	14.3	2.4	7.7	88.8	81.4	94.1	92.3
8	0.84	0.12	1.89	150	31	5.1	5.5	0.6	0.6	0.4	0.3	2020	110	5.1	–	4	16.5	6.8	5.3	88.4	92.1	92.4	94.1
9	0.82	0.08	1.88	–	–	6.7	6.7	0.6	1.3	0.4	0.4	2050	135	5.2	–	3	13.0	3.6	7.5	90.3	79.0	95.3	93.6
10	0.84	0.12	1.90	155	35	8.2	7.6	0.8	2.0	0.6	0.7	2185	155	5.2	14.4	4	22.0	4.8	5.9	88.9	72.2	91.5	90.3
11	0.75	0.05	2.20	178	24	5.9	4.9	0.6	0.8	0.5	0.4	2320	201	5.0	–	4	22.5	5.5	6.5	90.0	86.5	91.5	93.2
12	0.76	0.02	1.58	277	37	8.7	7.3	0.5	0.7	0.3	0.3	2200	209	5.3	13.8	5	25.5	4.0	11.1	94.3	94.3	96.5	96.6
13	0.89	0.83	1.03	250	53	4.9	5.1	0.9	2.8	0.5	0.6	2260	161	4.8	–	14	15.0	3.0	10.9	81.6	43.3	89.9	87.8
14	1.03	2.25	0.91	76	37	2.3	2.6	1.2	1.5	0.7	0.8	2220	210	4.3	12.6	26	8.0	2.0	3.9	48.0	21.7	69.7	65.2
15	1.16	1.00	1.18	172	22	3.0	3.0	1.1	2.0	0.6	0.7	2400	141	4.1	–	15	9.5	3.8	4.6	63.3	36.0	80.0	58.8
16	1.14	1.66	1.24	70	19	2.4	2.1	0.8	1.8	0.5	1.2	2690	96	4.1	11.7	14	9.0	1.9	3.2	66.6	25.3	79.0	50.0
17	1.08	2.47	1.60	352	30	1.9	1.9	1.1	1.6	0.5	0.7	3000	107	4.1	–	24	7.5	2.3	3.0	41.8	15.8	73.8	63.1

* FE – Final Effluent; PI – Primary Effluent; Bps – By Pass; MLS – Mixed Liquor Solids; SVI – Sludge Volume Index; + Including Ammonia

												ONE LEVEL DOSING – WASTING OF MIXED LIQUOR SOLIDS TO DRYING BEDS											
18	1.11	1.20	1.31	77	25	2.8	2.4	0.8	1.9	0.5	0.5	3350	84	4.0	11.3	10	9.5	1.8	5.7	71.6	32.1	82.3	82.0
19	0.93	0.90	1.36	137	25	4.5	4.7	0.8	2.5	0.5	0.7	3670	100	4.0	–	8	15.0	3.1	3.6	82.3	44.4	88.8	86.4
20	0.78	0.57	1.36	115	18	4.2	4.2	0.6	1.9	0.5	0.3	3450	103	3.9	9.6	8	12.5	2.0	1.6	85.9	61.9	88.1	92.8
21	0.87	0.34	1.41	146	16	5.2	4.6	0.8	1.8	0.5	0.3	3376	120	3.8	–	6	13.3	2.9	3.6	88.4	65.7	90.6	90.3
22	0.86	0.25	1.33	149	32	5.7	5.4	0.7	1.4	0.6	0.6	3321	130	4.1	–	WASTING OF RETURN SLUDGE TO DRYING BEDS 7	17.0	2.8	4.9	87.8	68.5	89.5	89.5
23	0.83	0.14	1.46	152	76	6.1	6.3	1.1	1.7	0.7	0.7	3590	97	4.4	–	4	16.5	3.8	4.2	82.7	73.1	88.8	88.8
24	0.90	0.12	1.30	127	26	4.4	3.9	1.3	2.4	0.5	1.0	3053	139	3.4	11.2	11	19.0	3.8	6.0	83.6	73.4	88.8	85.4
25	0.84	0.04	1.61	135	24	3.2	3.0	1.3	1.5	0.9	0.9	3600	115	4.1	–	7	17.0	2.9	8.5	82.0	79.2	87.4	87.6
26	0.87	0.07	1.62	198	35	6.2	7.5	1.8	2.2	0.5	0.5	3720	118	4.9	–	8	23.0	2.0	9.0	78.2	72.8	93.9	92.7
27	0.83	0.02	1.74	201	31	7.5	7.1	1.1	0.8	0.5	0.5	4180	112	4.0	–	5	18.8	1.9	10.9	89.7	89.1	93.7	93.7
28	0.84	0.01	1.62	184	34	6.4	6.6	1.0	0.8	0.6	0.6	4210	117	4.8	–	9	18.5	2.5	7.0	88.5	87.3	91.3	91.2
29	0.85	0.00	1.70	183	43	7.0	7.6	1.5	0.8	0.7	0.7	4110	122	4.3	–	9	21.0	2.5	10.0	88.5	88.5	90.0	90.0
30	0.82	0.00	1.21	193	35	8.1	8.1	1.8	1.3	1.2	1.2	ONE LEVEL DOSING – WASTING OF RETURN SLUDGE TO BOTH PRIMARIES 3930	93	4.6	9.3	5	20.5	2.8	13.9	83.6	83.6	85.0	85.0
31	0.80	0.00	1.20	224	15	8.2	7.6	1.7	1.7	1.5	1.5	3440	96	5.1	10.7	5	23.0	2.0	3.9	79.8	79.8	82.0	82.0
May 1-31	0.87	0.15	1.46	170	41	5.8	5.6	1.1	1.7	1.0	1.0	2896	132	4.7	–	13	16.6	3.3	6.7	81.0	71.4	88.3	85.7
May 1-31 but excluding May 3.	0.89	0.08	1.68	177	24	5.8	5.4	1.2	1.9	1.0	1.0	3028	120	4.7	–	8	19.6	2.4	5.6	84.2	74.2	88.1	85.5

** On May 3, inadvertant acceptance of 1.5:1.0 Mol rate for 2-1 hours raised effluent COD, suspended solids, and phosphorus for the day to 108, 151, and 8.3 mg/l respectively.

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TABLE VI. -- FERRIC AND FERROUS IRON TO PRIMARY EFFLUENT
Average Daily Values of Demonstration Periods
Single Level Dosing Rate Throughout Each Day, Except Where Otherwise Indicated

	Ferric Iron						Ferrous Iron				
Column Number	1	2	3	4	5	6	7	8	9	10	11
Period	Jan 29 - Feb 1 '69	Jan '70 2-7	Nov '69 23-30	Nov '69 15-22	Mar '69 8-15	Dec '69 1-4	Jan '69 21-28	Apr '69 5-9	Apr '69 25-30	Apr '69 10-18	Apr '69 19-24
Number of Days	4	6	8	8	8	4	8	5	*6	9	5
Flow, MGD											
Total	.74	.79	.51	.56	1.05	.45	.89	.72	.87	1.64	.84
Thru plant	.74	.77	.51	.51	.94	.45	.89	.68	.81	.92	.78
Dose, mol ratio, Fe/P (FMR)	.28	.81	1.16	1.35	1.41	1.60	.28	1.17	*1.32	1.32	1.37
Phosphorus, P, mg/l											
Total, raw influent	9.2	9.2	14.1	12.8	5.0	14.0	6.7	9.2	7.9	5.5	8.1
Total, prim effluent	8.8	8.5	14.9	13.2	5.2	15.4	7.0	10.5	8.1	6.6	8.4
Total, final effluent	8.3	3.8	3.7	5.4	1.1	2.9	4.4	2.3	1.0	1.1	1.7
Soluble, final effluent	5.7	3.0	3.1	3.9	0.7	2.5	3.9	1.3	0.7	0.6	1.3
Phosphorus, P, lbs/day											
Total, raw influent	56.7	59.4	60.0	54.5	39.2	52.6	49.7	52.2	50.0	42.5	52.7
Total, prim effluent	54.3	54.9	63.4	56.2	40.7	57.8	52.0	59.5	50.6	50.5	54.7
Total, final effluent	51.2	24.6	15.7	23.0	8.6	10.9	29.0	13.0	6.2	8.4	11.1
P, Removal, Effectiveness and Efficiency											
Across primary, %	4.	8.	-6.	-3.	-4.	-10.	-4.	-14.	-1.	-19.	-4.
Across plant, %	9.	59.	74.	58.	77.	79.	38.	75.	87.	80.	79.
Across plant, % insolubilized	49.	67.	80.	70.	85.	82.	44.	85.	91.	89.	84.
Effective Mol Ratios											
For removal (EMRr)	3.12	1.37	1.57	2.32	1.82	2.03	.74	1.56	1.51	1.65	1.73
For insolubilization (EMRi)	.57	1.20	1.45	1.93	1.66	1.95	.63	1.37	1.44	1.49	1.65
TSS											
Raw influent, mg/l	85.	134.	133.	143.	82.	118.	63.	80.	106.	100.	70.
Prim effluent, mg/l	85.	100.	110.	77.	62.	118.	53.	84.	76.	62.	73.
Final effluent, mg/l	98.	22.	10.	35.	10.	17.	22.	19.	7.	9.	10.
Raw influent lbs/day	524.	861.	566.	609.	643.	442.	468.	454.	663.	765.	455.
Prim effluent, lbs/day	524.	642.	468.	328.	486.	442.	393.	476.	475.	475.	475.
Final effluent, lbs/day	606.	144.	43.	149.	78.	64.	163.	108.	43.	71.	65.
Removal across primary, %	0.	26.	17.	46.	24.	0.	16.	-5.	28.	38.	-4.
Removal across plant, %	-15.	83.	92.	76.	88.	86.	66.	76.	93.	91.	86.
DO, Aeration effluent											
Av of daily peaks	2.4	1.0	3.4	3.5	4.1	2.5	2.2	2.2	2.0	3.0	2.6
Av of daily lows	.8	.3	.2	.2	.3	.2	.6	.2	.2	.4	.3
Av of bihourly rdgs	1.5	.6	1.1	1.4	1.5	.9	1.1	.9	.7	1.3	.9
pH Ranges											
Primary influent	7.3-7.6	-	7.5-7.6	7.4	7.4-7.6	7.4-7.6	7.3-7.5	7.4-7.5	7.2-7.6	7.5	7.5
Aeration influent	7.3-7.6	-	-	7.1	7.3-7.4	7.2	7.1-7.6	-	-	7.4	7.4
Aeration effluent	7.5-7.7	7.6-7.6	7.3	7.3	7.3-7.4	7.2-7.5	7.3-7.7	7.4-7.5	7.2-7.5	7.4-7.5	7.5
Aeration solids											
MLS, mg/l	1280.	2654.	2153.	2205.	2188.	1993.	1408.	1843.	2439.	2208.	2065.
Sludge volume index (SVI)	604.	137.	258.	362.	104.	190.	278.	86.	97.	83.	73.
Phosphorus in solids, %P	3.4	4.2	4.7	3.5	3.6	5.4	2.6	5.6	5.4	4.8	5.2
COD											
Raw influent, mg/l	235.	293.	355.	318.	125.	354.	196.	238.	227.	163.	194.
Prim effluent, mg/l	216.	219.	280.	256.	100.	272.	172.	195.	169.	117.	160.
Final effluent, mg/l	114.	44.	37.	63.	22.	27.	49.	40.	31.	31.	33.
Raw influent, lbs/day	1468.	1880.	1515.	1350.	973.	1335.	1450.	1326.	1544.	1255.	1264.
Prim effluent, lbs/day	1350.	1410.	1194.	1088.	779.	1026.	1270.	1086.	1150.	906.	1042.
Final effluent, lbs/day	712.	281.	158.	267.	171.	102.	361.	222.	211.	243.	215.
Removal across primary, %	8.	29.	23.	19.	20.	23.	12.	18.	18.	28.	18.
Removal across plant, %	51.	83.	85.	80.	82.	92.	75.	83.	86.	81.	83.
Lbs COD/day/lbs. aeration solids	.64	.30	.39	.34	.25	.37	.57	.40	.35	.31	.34
Nitrogen											
Total N, raw influent, mg/l	19.2	26.0	30.0	32.0	12.6	35.3	15.6	21.8	26.5	13.6	19.0
**Kjldl, final effluent, mg/l	12.6	16.0	6.0	4.5	1.8	4.3	7.8	5.0	4.8	3.8	5.2
NO3-N, final effluent, mg/l	3.7	.3	15.7	13.2	5.0	13.0	2.1	8.0	7.3	4.4	5.4
Total N, final effluent, mg/l	16.3	16.3	19.7	17.7	6.8	17.3	9.7	13.0	12.1	8.3	10.6
Removal, total N, mg/l	2.9	9.7	16.3	14.3	5.9	18.0	5.9	8.8	14.3	5.3	8.4
Removal, total N, %	15.	37.	45.	45.	47.	51.	38.	40.	54.	39.	44.

* Two level dosing rate each day

** Including ammonia

TABLE VII. – FERRIC AND FERROUS TO RAW INFLUENT
Average Daily Values of Demonstration Periods
Single level dosing rate throughout each day, except where otherwise indicated

	FERRIC IRON							FERROUS IRON				
Column number	1	2	3	4	5	6	7	8	9	10	11	12	13
Period, 1969	Dec 28-Jan 1	Feb 18-20	Feb 26-Mar 2	March 3-7	Dec 5-12	Dec 13-15	Dec 24-27	Mar 29-Apr 4	June 8-13	May 19-29	June 1-7	Dec 16-23	May 4-13
Number of days	5	3	5	5	8	3	4	7	6	11	7	8	*10
Flow, MGD													
Total	.63	1.15	1.27	1.95	1.80	.88	.64	.82	.78	1.09	1.11	.73	1.15
Thru plant	.63	1.00	.98	.97	.89	.88	.64	.79	.78	.87	.94	.73	.87
Dose, mol ratio, Fe/P													
Appl	.80	1.02	1.04	1.40	1.43	1.56	1.75	1.09	1.31	1.50	1.58	1.62	*1.60
Phosphorus, P, mg/l													
Total, raw influent	10.9	5.3	5.0	3.9	5.2	8.4	9.9	8.7	8.4	6.4	5.8	9.2	5.9
Total, primary effluent	9.3	4.9	4.7	3.6	5.2	6.3	7.3	8.5	8.6	6.1	5.8	7.4	5.8
Total, Final effluent	3.5	1.7	1.8	.9	2.1	1.8	1.6	2.3	1.4	1.0	.7	1.5	.7
Soluble, Final Effluent	3.2	1.1	1.5	.7	1.3	1.2	1.3	1.0	1.2	.6	.5	1.1	.5
Phosphorus, P, lbs/day													
Total raw influent	57.4	44.2	40.0	32.3	38.6	61.1	52.8	57.3	54.7	46.5	45.8	56.0	42.8
Total prim effluent	49.0	40.8	37.6	29.1	38.6	46.0	39.0	56.0	56.0	44.3	45.5	45.0	42.1
Total final effluent	18.5	14.2	14.4	7.3	15.6	12.8	8.5	15.2	9.1	7.2	5.7	9.1	5.1
P, Removal, effectiveness and efficiency													
Across primary, %	15.	7.	6.	10.	0	25.	26.	2.	-7.	5.	0	20.	2.
Across plant, %	68.	68.	62.	76.	59.	79.	84.	74.	83.	85.	88.	84.	88.
Across plant, % insolubilized	71.	79.	70.	83.	75.	85.	87.	89.	86.	89.	91.	88.	92.
Effective mol ratios													
For removal (EMRr)	1.18	1.50	1.67	1.87	2.40	1.98	2.08	1.48	1.57	1.76	1.81	.193	1.84
For insolubilization (EMRi)	1.13	1.29	1.48	1.69	1.95	1.83	2.01	1.23	1.53	1.68	1.74	.177	1.72
TSS													
Raw, influent, mg/l	71.	73.	128.	112.	116.	82.	112.	65.	146.	118.	130.	71.	137.
Prim effluent, mg/l	104.	80.	96.	94.	103.	110.	102.	135.	157.	94.	116.	115.	92.
Final effluent, mg/l	8.	18.	8.	11.	31.	9.	7.	30.	6.	7.	7.	9.	6.
Raw influent, lbs/day	368.	608.	1025.	907.	860.	599.	598.	428.	950.	856.	1020.	433.	994.
Prim effluent, lbs/day	548.	667.	768.	760.	764.	804.	550.	890.	1022.	683.	912.	700.	668.
Final effluent, lbs/day	42.	133.	64.	89.	245.	64.	37.	197.	26.	51.	53.	55.	44.
***Removal across primary, %	-46.	-10.	25.	18.	10.	-34.	9.	-108.	-8.	20.	11.	-62.	33.
Removal across plant, %	61.	78.	94.	90.	72.	89.	94.	54.	99.	94.	95.	87.	96.
DO, Aeration effluent													
Av of daily peaks	1.4	4.1	3.3	5.8	3.6	2.2	1.0	3.1	1.7	2.5	3.0	2.3	2.2
Av of daily lows	.4	.7	.5	.3	.2	.2	.4	1.2	.5	.3	.4	.5	.3
Av of hrly rdgs	.7	2.0	1.6	3.0	1.5	.8	.7	.4	.9	1.0	1.0	1.0	.8
pH ranges													
Primary influent	7.3	7.1-7.3	7.2-7.3	7.1-7.2	7.0-7.3	7.1-7.3	7.1-7.4	7.2-7.5	7.3-7.4	7.0-7.3	7.1-7.4	7.1-7.5	7.1-7.5
Aeration influent	7.5-7.6	7.3-7.6	7.3	7.2-7.3	7.2	7.3	7.3-7.4	7.3-7.4	7.3-7.4	-	7.4-7.5	7.2	7.4
Aeration effluent	7.6-7.7	7.3-7.6	7.4	7.4-7.5	7.3-7.5	7.1-7.4	7.5-7.7	7.3-7.5	7.3-7.6	7.3-7.5	7.4-7.5	7.3-7.6	7.4-7.5
Aeration solids													
MLSS, mg/l	2631.	2557.	2319.	2130.	2078.	2503.	2654.	2583.	1946.	3771.	2702.	2468.	2122.
Sludge volume index (SVI)	135.	145.	166.	123.	106.	79.	91.	94.	65.	113.	74.	73.	137.
Phosphorus in solids, %P	4.4	3.3	2.9	3.0	4.5	3.8	4.9	5.0	4.8	4.4	4.4	4.5	5.1
COD													
Raw influent, mg/l	268.	147.	183.	133.	200.	171.	275.	212.	240.	165.	179.	213.	183.
Prim effluent, mg/l	261.	139.	161.	115.	139.	143.	218.	186.	264.	141.	154.	145.	126.
Final effluent, mg/l	51.	44.	27.	34.	47.	22.	33.	41.	33.	25.	24.	24.	37.
Raw influent, lbs/day	1405.	1228.	1459.	1079.	1490.	1250.	1475.	1397.	1600.	1190.	1405.	1279.	1333.
Prim effluent, lbs/day	1367.	1159.	1126.	930.	1035.	1045.	1169.	1225.	1720.	1019.	1214.	885.	919.
Final effluent, lbs/day	173.	368.	210.	277.	350.	161.	113.	270.	215.	180.	190.	145.	267.
Removal across primary, %	3.	5.	24.	13.	30.	16.	21.	12.	-7.	14.	13.	32.	31.
Removal across plant, %	88.	70.	85.	74.	76.	87.	92.	81.	88.	85.	87.	89.	80.
lbs COD/day/lbs aeration solids	.30	.30	.35	.28	.40	.28	.31	.30	.39	.18	.29	.29	.35
Nitrogen													
Total N, raw influent, mg/l	29.5	13.1	15.2	10.5	15.2	22.4	29.7	19.7	26.6	17.4	14.3	25.4	18.0
**Total, final effluent, mg/l	18.2	2.7	2.0	1.7	3.1	3.4	15.7	2.7	8.1	2.7	3.6	7.8	4.5
NH_3-N, final effluent, mg/l	.4	1.8	1.1	5.4	7.5	9.0	1.6	6.9	3.9	6.5	6.5	6.9	6.6
Total N, final effluent, mg/l	18.6	4.2	3.1	7.2	10.6	12.4	17.3	9.6	12.0	9.2	10.1	14.7	11.1
Removal, total N, mg/l	10.9	8.9	10.0	3.3	4.6	10.0	12.4	10.1	14.6	8.2	4.2	10.7	8.9
Removal, total N, %	37.	68.	78.	31.	30.	45.	42.	51.	55.	47.	29.	42.	50.

* Two level dosing rate each day

** Including ammonia

***Samples of primary effluent were not analyzed immediately, but were accumulated one day for compositing and analysis on the following day. The continuing precipitation of iron and phosphate in the samples before compositing and analysis, resulted in these low, sometimes negative, apparent removals of TSS.

TABLE VIII — FERRIC AND FERROUS IRON TO PRIMARY EFFLUENT
AND TO RAW INFLUENT
Effectiveness at Increasing Mol Doses, Fe/P

Period, 1969 except where noted otherwise	Days	Average Daily Values for Respective Periods							
		Phosphorus mg/l P			Dose	Rmvd	Insolu-	EMRr	EMRi
		Total Raw	Total Final Effl	Sol Final Effl	Fe/P AMR	P %	bilized %		
Ferric to Primary Effluent									
Jan 29-Feb 1	4	9.2	8.3	5.7	.28	9	49	3.1	.57
Jan 2-7 1970	6	9.2	3.8	3.0	.80	59	68	1.36	1.18
Nov 23-30	8	14.1	3.7	3.1	1.16	74	80	1.56	1.45
Nov 15-22	8	12.8	5.4	3.9	1.35	58	70	2.32	1.93
Mar 8-15	8	5.0	1.1	0.7	1.41	77	82	1.83	1.76
Dec 1-4	4	14.0	2.9	2.5	1.60	79		2.02	1.95
Ferrous to Primary Effluent									
Jan 21-28	8	6.7	4.4	3.9	.28	38	44	.74	.64
Apr 5-9	5	9.2	2.3	1.3	1.17	75	85	1.56	1.38
Apr 25-30*	6	7.9	1.0	0.7	*1.32	*87	91	1.52	1.45
Apr 10-18	9	5.5	1.1	0.6	1.34	80	89	1.52	1.50
Apr 19-24	6	8.1	1.7	1.3	1.38	79	84	1.75	1.64
Ferric to Raw Influent									
Dec 23 1969-Jan 1 1970	5	10.9	3.5	3.2	.80	68	71	1.18	1.13
Feb 18-20	3	5.3	1.7	1.1	1.02	68	79	1.50	1.29
Feb 26-Mar 2	5	5.0	1.8	1.5	1.04	62	70	1.68	1.49
Mar 3-7	5	3.9	.9	.7	1.40	77	82	1.82	1.71
Dec 5-12	8	5.2	2.1	1.3	1.43	58	75	2.47	1.91
Dec 13-15	3	8.4	1.8	1.2	1.56	79	85	1.98	1.83
Dec 24-27	4	9.9	1.6	1.3	1.80	84	87	2.14	2.07
Ferrous to Raw Influent									
Mar 29-Apr 4	7	8.7	2.3	1.0	1.10	74	89	1.49	1.24
June 8-13	6	8.4	1.4	1.2	1.31	84	86	1.56	1.52
May 19-29	11	6.4	1.0	0.6	1.50	85	91	1.76	1.65
June 1-7	7	5.8	0.7	0.5	1.59	88	91	1.80	1.75
Dec 16-23	8	9.2	1.5	1.1	1.60	84	88	1.90	1.82
May 4-13**	10	5.9	.7	.5	**1.60	**88	92	1.82	1.74

*April 25-30 dosage was at a diurnal two-level rate. All other dosing of ferric and ferrous iron to primary effluent was at a single-level rate.

**May 4-13 dosage was at a diurnal two-level rate. All other dosing of ferric and ferrous iron to raw influent was at a single-level rate.

TABLE IX. – REMOVAL OF PHOSPHORUS WITH LIME TO RAW INFLUENT AND TO RETURN SLUDGE SUMP
Daily Averages of Operation and Index Parameters
July 15-19 and July 29-Aug. 5, 1969

Date July-Aug. 1969	Flow MGD	Mol Dose Lime/P	COD mg/l Raw	COD mg/l FE*	Total P. mg/l Raw	Total P. mg/l PE*	Total P. mg/l FE*	Sol. P mg/l FE*	TSS mg/l FE*	Aeration Solids mg/l MLS*	Aeration Solids SVI*	Aeration Solids % P Dry	Aeration Solids %Ca Dry	Aeration Solids %Mg Dry	Kjldl N** mg/l Raw	Kjldl N** mg/l FE*	NO_3-N mg/l FE*	%P Rmvd*	pH Values Raw	pH Values PE*	pH Values Aerat. Inf.	pH Values Aerat. Eff.
										NO LIME ADDED												
10	.488	0	347	36	12.0	11.4	9.4	9.4	6	1448	460	1.6	-	-	24.0	3.5	8.2	22	-	-	-	-
11	.439	0	327	24	10.8	10.8	9.8	9.3	1	1450	480	1.6	1.5	.3	28.0	2.3	9.0	9	7.55	7.45	7.50	7.50
12	.490	0	338	29	11.4	11.0	9.0	8.7	9	1405	460	1.6	2.7	.6	25.0	2.3	14.9	21	-	-	-	-
13	.485	0	229	27	9.5	9.5	9.0	9.0	4	1440	430	1.3	1.4	.3	26.0	2.3	6.0	5	-	-	-	-
14	.465	0	307	21	11.7	11.9	9.3	9.2	3	1430	320	1.4	2.0	.6	25.0	2.3	14.9	20	-	-	-	-
Av.	.473	0	310	27	11.1	10.9	9.3	9.1	5	1435	430	1.5	1.9	.4	25.6	2.5	10.6	15	-	-	-	-
										LIME ADDED TO RETURN SLUDGE IN SLIP-VALVE SUMP												
15	.595	1.7	350	22	11.4	11.0	10.1	9.8	10	1495	290	1.4	-	.2	25.0	4.0	5.9	11	7.70	7.55	8.15	7.60
16	.553	4.2	323	34	9.0	9.3	7.7	7.2	6	1845	210	1.4	3.9	.2	23.0	2.0	6.9	14	7.40	7.45	8.10	7.65
17	.475	3.8	307	23	11.7	12.0	8.4	8.2	5	1680	190	1.6	5.6	.2	30.0	6.0	12.5	28	7.55	7.50	8.15	7.60
18	.469	3.4	275	40	13.1	12.7	10.8	10.3	9	1798	150	1.7	3.4	.3	27.0	3.0	9.0	18	7.60	7.55	8.25	7.90
19	.454	2.1	306	30	13.8	13.8	10.8	10.6	1	1830	140	1.5	5.4	.2	30.6	4.0	10.0	22	7.45	7.50	8.35	7.80
Av.	.509	3.0	312	30	11.8	11.8	9.6	9.2	6	1528	226	1.5	4.6	.2	27.1	3.8	8.8	19	-	-	-	-
										NO LIME ADDED												
20	.489	0	290	30	11.4	11.2	10.8	10.8	5	1795	120	1.4	-	-	30.5	2.3	15.6	5	-	-	-	-
21	.510	0	322	34	14.4	13.8	10.4	10.1	7	1715	110	1.4	3.0	.3	32.0	2.8	13.4	28	7.35	7.40	7.55	7.50
22	.500	0	239	26	12.2	12.7	11.2	11.0	8	1675	110	1.4	3.0	.2	27.0	2.3	9.5	8	7.45	7.45	7.50	7.45
23	.530	0	331	29	12.2	12.5	10.6	10.1	6	1693	120	1.5	2.4	.2	28.0	2.3	9.0	13	-	-	-	-
24	.502	0	417	40	12.9	12.4	10.8	10.4	7	1960	140	1.4	2.4	.2	31.5	3.0	5.0	16	-	-	-	-
25	.539	0	357	36	12.0	13.1	11.5	11.2	6	1748	270	1.3	2.5	.2	27.5	5.8	2.8	4	7.40	7.55	7.60	7.65
26	.558	0	-	-	12.9	12.9	11.4	11.4	4	1730	290	1.3	1.8	.2	35.0	4.8	4.8	12	-	-	-	-
27	.545	0	324	41	10.8	11.0	10.6	10.6	3	1610	340	1.6	2.4	.4	27.5	3.8	6.2	2	-	-	-	-
28	.535	0	221	15	12.2	12.4	9.8	9.5	4	1733	310	1.5	2.4	.2	27.0	4.0	6.2	20	7.35	7.30	7.50	7.50
Av.	.523	0	294	30	11.2	12.4	10.8	10.8	6	1743	205	1.4	2.2	.2	29.5	3.4	8.1	12	-	-	-	-
										LIME ADDED TO RAW INFLUENT												
29	.536	2.2	223	17	11.4	12.0	11.4	11.0	6	1673	380	1.4	2.6	.4	28.0	3.5	1.3	0	7.40	7.40	7.55	7.50
30	.529	3.7	347	25	12.0	11.0	10.1	10.1	6	1865	360	1.5	3.5	.3	28.5	2.3	5.0	16	7.40	8.60	8.30	8.05
31	.503	3.5	280	20	13.1	10.4	10.8	9.3	5	1758	443	1.2	2.3	.2	29.5	2.3	8.0	18	7.40	8.65	8.10	7.60
Aug. 1	.496	3.6	273	25	13.1	10.1	9.5	9.8	6	1730	446	1.2	3.0	.3	31.0	2.8	7.1	27	7.90	8.30	8.10	7.65
2	.519	4.0	250	18	13.4	12.0	10.1	9.5	5	1615	473	1.4	3.2	.2	30.0	6.8	8.2	25	-	-	-	-
3	.493	5.1	315	25	10.9	7.9	9.8	9.8	13	1585	512	1.5	2.9	.3	33.0	6.5	6.6	10	7.40	8.80	8.35	7.60
4	.497	4.6	236	11	15.6	10.8	9.0	9.0	7	1653	496	1.7	-	.4	28.0	4.0	13.5	42	7.40	8.65	8.40	7.60
5	.486	8.4	298	29	12.7	7.2	8.7	8.4	5	1563	518	1.5	-	.3	32.5	4.5	9.3	31	7.40	9.15	8.25	7.80
Av.	.507	4.4	270	21	12.7	10.4	10.0	9.7	7	1564	489	1.4	2.9	.3	30.0	4.0	6.9	20	-	-	-	-

*PE-Primary effluent; FE-Final effluent; MLS-Mixed liquor solids; SVI-Sludge volume index; Rmvd-Removed

**Including ammonia

TABLE X. — REMOVAL OF PHOSPHORUS WITH ALUMINUM CHLORIDE,
INJECTED TO RAW INFLUENT AND TO PRIMARY EFFLUENT
Daily Averages of Operation and Index Parameters, plus Averages of Sequential Periods
Aug. 21 - Oct. 15, 1969
Period averages are not weighted according to flow except where indicated as "wt. av."

Date 1969	Flow MGD	Mol Dose Al/P	COD mg/l		Total P. mg/l			Sol. P mg/l	TSS mg/l	Aeration Solids				Kjldl N** mg/l		NO_3-N mg/l	%P Rmvd	%P to Slds
			Raw	FE*	Raw	PE*	FE	PE	FE	MLS*	SVI*	%P Dry	% Al Dry	Raw	FE	FE		
								TO RAW INFLUENT										
Aug. 21	.696	.462	369	53	7.9	7.7	8.7	8.5	16	1375	429	1.6	.38	25.0	2.5	13.9	-9	-8
22	.882	.99	223	40	8.9	8.4	3.4	3.1	13	1495	294	2.0	-	22.5	6.3	4.6	62	65
23	.867	1.23	146	42	7.2	7.7	3.7	2.8	11	1665	234	2.3	-	18.0	3.0	5.4	49	61
24	.690	1.11	229	34	10.1	10.3	3.6	3.4	8	2050	215	2.7	-	25.0	2.5	6.2	64	66
25	.555	1.20	281	33	11.5	12.7	3.4	3.4	7	2015	233	3.4	-	29.5	2.0	13.4	71	71
26	.485	1.39	235	28	12.4	12.5	3.6	3.2	8	2253	204	3.6	1.4	28.0	1.5	11.5	71	74
27	.575	1.31	278	52	11.0	12.7	3.7	3.6	7	2630	220	3.8	-	28.0	2.5	12.2	66	67
Period Av.	.576	1.25	255	37	11.2	12.1	3.6	3.4	8	2170	218	3.4	-	27.0	2.1	10.8	68	70
Aug. 24-27																		
28	1.025	.98	352	33	5.3	5.6	2.9	2.4	18	2285	153	3.8	-	16.0	1.5	1.5	45	55
29	.831	2.24	155	19	6.8	4.3	2.1	1.8	3	2160	130	3.8	-	29.0	3.1	5.6	69	74
30	.587	[illegible]	295	29	11.4	6.2	2.5	2.4	5	2190	119	3.7	-	21.5	2.5	10.8	78	79
31	.464	[illegible]	221	37	8.3	3.8	3.4	2.8	15	2160	110	3.6	-	25.0	7.1	6.8	59	66
Sept. 1	.486	1.60	233	11	13.1	6.7	2.8	2.3	3	1910	120	3.6	1.9	42.0	3.5	4.0	79	83
2	.546	1.75	340	30	13.4	5.9	3.2	2.9	13	1877	107	3.4	-	45.0	2.3	15.0	77	78
Period Av.	.657	1.82	266	26	9.7	5.4	2.8	2.4	9	2097	123	3.6	-	29.7	3.3	4.6	71	75
Wt. Av.	-	2.04	270	27	9.0	5.4	2.8	2.4	9	2127	128	3.7	-	27.8	3.0	5.8	69	71
Sept. 3	.545	1.75	380	32	12.9	8.4	3.7	3.2	6	1710	117	3.9	-	34.0	1.5	5.7	71	75
4	.565	1.81	345	32	11.0	9.5	2.1	2.1	7	2107	100	3.7	-	28.0	1.5	13.6	81	81
5	.517	1.88	400	34	12.7	10.4	2.9	2.5	11	2100	114	4.0	-	28.8	1.9	11.8	77	80
6	.508	1.77	299	41	13.7	7.3	3.4	3.1	4	2000	115	4.3	-	28.0	2.3	13.7	75	78
7	.547	1.72	283	34	11.0	7.3	4.0	3.4	5	1980	120	4.0	-	22.2	2.0	16.0	64	69
8	.532	1.82	341	34	13.8	9.5	3.4	2.9	4	1945	123	4.2	2.8	33.5	1.5	12.2	75	79
Period Av.	.536***	1.79	341	34	12.5	8.7	3.3	2.9	6	1974	115	4.0	-	29.1	1.8	12.2	74	77
								TO PRIMARY EFFLUENT										
Sept. 9	.527	1.68	384	39	12.0	13.1	2.3	2.1	4	2140	216	4.4	-	29.5	2.8	10.0	81	83
10	.498	1.58	396	39	12.0	13.8	2.5	2.3	7	2282	136	4.5	3.3	29.5	1.9	12.0	79	81
11	.442	1.44	396	38	14.2	14.2	2.8	2.2	9	2317	142	4.6	-	32.0	1.3	14.7	80	85
12	.442	1.65	363	38	14.7	15.4	2.9	2.3	5	2270	146	5.2	-	34.5	2.5	10.6	80	85
13	.521	1.88	365	33	14.5	16.3	2.5	2.1	9	2430	136	5.1	-	32.3	1.5	13.4	83	86
Period Av.	.486***	1.65	381	37	13.5	14.6	2.6	2.2	7	2288	155	4.8	-	31.6	2.0	12.1	81	84
Sept. 14	.467	2.02	412	38	13.4	13.8	2.5	1.9	10	2510	155	5.2	-	35.0	2.5	9.4	81	86
15	.495	2.06	363	29	14.4	15.6	2.2	1.4	13	2500	140	5.3	-	34.0	2.3	13.6	85	90
16	.491	2.22	353	32	12.2	14.5	2.6	1.8	9	2490	156	5.5	-	31.0	2.0	11.5	79	85
17	.523	2.17	323	48	10.6	13.1	2.2	1.9	16	2490	137	5.3	4.9	26.5	1.6	10.8	79	82
18	.541	1.63	433	48	13.7	14.6	2.0	1.5	9	2435	128	5.5	-	23.0	2.3	7.8	86	89
Period Av.	.503***	2.02	377	39	12.9	14.3	2.3	1.7	11	2485	143	5.4	-	29.9	2.1	10.6	82	87
Sept. 19	.480	2.30	439	40	14.9	14.9	2.1	1.3	6	2522	147	5.7	-	33.0	3.5	9.8	86	91
20	.487	2.60	505	57	14.6	17.6	3.0	1.1	37	2670	161	5.6	4.3	24.5	1.8	10.6	80	93
21	.487	2.10	422	60	13.8	15.2	3.3	1.2	39	2790	136	5.3	-	33.0	2.5	10.2	76	91
22	.473	2.60	422	40	13.8	16.3	2.8	.9	32	2687	134	5.4	-	37.5	3.8	12.5	80	93
23	.465	2.46	414	52	12.9	14.9	2.6	1.2	27	2640	118	5.5	6.1	32.0	2.5	11.0	80	91
Period Av.	.478***	2.41	440	48	14.0	15.8	2.8	1.1	28	2662	139	5.5	-	32.0	2.8	10.8	80	92
Sept. 24	.432	2.52	443	48	13.8	16.3	2.3	0.7	26	2707	126	5.6	-	29.0	2.3	13.9	83	95
25	.477	2.33	445	38	13.8	15.4	2.8	1.0	28	2830	120	5.7	5.9	32.0	2.5	16.4	80	93
26	.461	2.54	353	44	14.2	16.3	3.4	1.2	29	2785	108	5.9	-	32.0	3.8	8.7	76	92
27	.516	2.01	409	37	17.2	19.2	3.5	1.2	50	3065	101	5.5	-	35.0	2.8	7.3	80	93
28	.433	2.52	398	41	13.9	16.7	2.8	1.1	30	2995	102	5.3	-	37.5	3.8	8.2	80	92
29	.564	2.52	365	36	14.9	19.7	3.4	1.1	42	2987	102	5.6	-	33.5	2.4	15.3	77	92
30	.450	2.81	500	43	13.1	19.2	3.6	1.2	40	2730	103	5.9	5.4	34.0	1.5	8.7	73	91
Oct. 1	.443	2.39	396	47	14.1	19.1	3.2	1.2	46	2608	92	5.8	-	33.5	3.0	13.2	77	92
Period Av.	.478	2.41	414	42	14.4	17.7	2.8	1.1	34	2838	107	5.7	-	33.3	2.8	11.5	80	92
Oct. 2	.450	2.05	394	45	15.8	17.2	2.9	1.1	32	2150	93	6.0	-	31.0	2.0	14.5	82	93
3	.516	1.85	408	25	17.9	17.2	2.7	1.1	18	1612	90	6.0	-	38.5	2.8	16.8	85	94
4	.500	2.05	394	53	17.2	17.2	2.3	1.2	30	1720	88	5.7	8.1	34.0	3.8	11.5	86	93
5	.470	2.30	379	65	13.8	15.8	3.8	1.7	42	2010	64	5.8	-	45.0	3.8	13.4	73	88
6	.439	2.75	377	23	14.9	17.6	2.7	1.3	30	2200	91	5.8	-	35.0	2.0	17.5	82	91
Period Av.	.475	2.20	309	42	15.9	17.0	2.9	1.3	30	1938	85	5.9	-	36.7	2.9	14.7	82	92
								Polyelectrolyte to Aeration Effluent										
Oct. 7	.461	2.52	396	29	14.2	16.7	1.3	1.4	8	2322	82	5.9	-	33.0	1.9	10.0	91	90
8	.474	2.27	438	33	14.5	14.4	1.4	1.1	12	2150	85	5.9	-	35.0	2.5	12.5	91	93
9	.562	2.86	283	36	9.3	10.1	1.1	0.8	0	1920	67	5.8	7.8	25.0	1.5	15.3	88	91
10	.684	2.53	313	35	9.5	10.4	0.8	0.5	5	1945	91	5.7	6.7	23.0	2.5	9.4	92	95
Period Av.	.545	2.55	357	33	11.9	12.9	1.1	1.0	6	2084	86	5.8	-	29.0	2.1	15.8	91	92
Wt. Av.	-	2.56	350	34	11.5	12.5	1.2	.9	6	2063	87	5.8	-	32.4	2.1	13.0	91	92
Oct. 11	.735	2.02	299	47	13.8	13.8	3.2	1.6	41	1700	92	5.6	-	29.0	3.3	9.8	77	89
12	.479	2.00	634	49	16.3	14.2	3.4	1.2	36	2005	94	5.0	-	39.5	7.3	6.2	79	93
13	1.156	1.49	354	36	10.8	11.7	3.0	0.8	44	2035	78	5.0	-	21.3	5.3	6.2	72	93
14	.453	2.54	343	70	14.2	15.4	5.0	0.9	70	2060	67	5.2	-	30.0	4.8	11.8	65	94
15	.457	3.00	338	84	13.4	16.3	6.9	1.2	96	1957	70	5.0	-	33.5	3.8	20.6	49	91
Period Av.	.656	2.21	394	57	13.7	14.3	4.3	1.1	63	1951	80	5.2	-	30.7	4.9	10.9	68	92

* FE - Final effluent; PE - Primary effluent; MLS - Mixed liquor solids; SVI - Sludge volume index; RMVD - Removed
** Including ammonia
*** Two level dosing rate, Sept. 3-23

TABLE XI. – ALUMINUM CHLORIDE TO RAW INFLUENT AND TO PRIMARY EFFLUENT

Average Daily Values of Demonstration Periods

Column No.	Raw Influent 1	2*	3	4**	Primary Effluent 5*	6*	7	8	9	10*	11***	12**
Period 1969	Aug 24-27	Sept 3-8	Aug 28- Sept 2	Aug 28- Sept 2	Sept. 9-13	Sept 14-18	Oct 2-6	Oct 11-15	Sept 24 Oct 1	Sept 19-23	Oct 7-10	Oct 7-10
Number of days	4	6	6	6	5	5	5	5	7	5	4	4
Flow, MGD												
Total	.576	.536	.853	.853	.486	.503	.475	.656	.478	.478	.545	.545
Thru plant	.576	.536	.657	.657	.486	.503	.475	.656	.478	.478	.545	.545
Dose, mol ratio, Al/P (AMR)	1.25	1.79*	1.81	2.04	1.65*	2.02*	2.20	2.21	2.41	2.41*	2.55	2.56
Phosphorus, P, mg/l												
Total, raw influent	11.2	12.5	9.7	9.0	13.5	12.9	15.9	13.7	14.4	14.0	11.9	11.5
Total, primary effluent	12.1	8.7	5.4	5.4	14.6	14.3	17.0	14.3	17.7	15.8	12.9	12.5
Total, final effluent	3.6	3.3	2.8	2.8	2.6	2.3	2.9	4.3	2.8	2.8	1.1	1.2
Soluble, final effluent	3.4	2.9	2.4	2.4	2.2	1.7	1.3	1.1	1.1	1.1	1.0	.9
Phosphorus, P, lbs/day												
Total, raw influent	53.8	55.9	53.2	49.3	54.8	54.1	63.1	75.0	57.5	55.9	54.2	52.3
Total, primary effluent	58.1	39.0	29.6	29.6	59.2	60.0	67.4	78.2	70.7	63.0	58.6	56.9
Total, final effluent	17.3	14.8	15.3	15.3	10.6	9.7	11.5	23.5	11.2	11.2	5.0	5.5
P, Removal, Effectiveness and Efficiency												
Across primary, %	-7.	30.	44.	40.	-7.	-11.	-7.	-4.	-24.	-13.	-8.	-9.
Across plant, %	68.	74.	71.	69.	81.	82.	82.	68.	80.	80.	91.	91.
Across plant, % insolubilized	70.	77.	75.	71.	84.	87.	92.	92.	92.	92.	92.	92.
Effective Mol Ratios												
For removal (EMRr)	1.84	3.42	3.37	3.14	2.03	2.46	2.68	3.25	3.01	3.01	2.80	2.81
For insolubilization (EMRi)	1.79	2.32	2.43	2.87	1.97	2.32	2.39	2.40	2.62	2.62	2.77	2.76
TSS												
Raw influent, mg/l	114.	120.	149.	145.	140.	151.	151.	230.	151.	191.	142.	143.
Primary effluent, mg/l	82.	135.	73.	78.	104.	91.	130.	152.	158.	132.	102.	100.
Final effluent, mg/l	8.	6.	9.	9.	7.	11.	30.	63.	34.	28.	6.	6.
Raw influent, lbs/day	548.	537.	816.	904.	567.	634.	598.	1260.	602.	763.	645.	650.
Prim effluent, lbs/day	395.	604.	400.	427.	422.	382.	514.	830.	630.	527.	463.	454.
Final effluent, lbs/day	39.	27.	49.	49.	28.	46.	119.	345.	136.	112.	27.	27.
Removal across primary,	28.	-12.	51.	53.	26.	40.	14.	34.	-5.	31.	28.	30.
Removal across plant, %	93.	95.	94.	95.	95.	93.	80.	73.	77.	85.	96.	96.
DO, Aeration Effluent												
Average of daily peaks	3.0	3.5	4.7	4.3	3.6	3.2	2.8	3.1	2.4	2.7	3.2	3.2
Average of daily lows	.3	.3	.2	.2	.2	.3	.3	.3	.2	.2	.3	.3
Average of bihourly readings	1.2	1.5	1.5	1.5	1.0	1.0	1.2	1.2	1.1	1.4	1.4	1.4
pH Ranges												
Primary influent	7.4-7.5	7.0-7.4	7.3-7.4	-	7.2-7.5	7.4-7.8	7.4-7.6	8.0	7.4-7.5	7.4-7.8	7.3-7.7	-
Aeration influent	7.4-7.5	7.1-7.4	7.1-7.2	-	7.0-7.3	7.0-7.3	7.0	6.9	7.0-7.2	7.0-7.2	7.0	-
Aeration effluent	7.4-7.6	7.2-7.4	7.2-7.5	-	7.4-7.5	7.1-7.2	7.0-7.1	7.0	7.1	7.1-7.3	7.1-7.2	-
Aeration Solids												
MLS, mg/l	2170.	1974.	2097.	2137.	2288.	2485.	1938.	1951.	2838.	2662.	2084.	2063.
Sludge volume index (SVI)	218.	115.	123.	128.	155.	143.	83.	80.	107.	139.	86.	87.
Phosphorus in solids, %P	3.4	4.0	3.6	3.7	4.8	5.4	5.9	5.2	5.7	5.5	5.8	5.8
COD												
Raw influent, mg/l	255.	341.	264.	270.	381.	377.	390.	394.	414.	440.	357.	350.
Prim effluent, mg/l	209.	245.	154.	164.	292.	280.	290.	278.	301.	323.	249.	244.
Final effluent, mg/l	37.	34.	26.	27.	37.	39.	42.	57.	42.	48.	33.	34.
Raw influent, lbs/day	1225.	1529.	1439.	1480.	1545.	1582.	1546.	2155.	1654.	1755.	1625.	1594.
Prim effluent, lbs/day	1004.	1098.	845.	900.	1185.	1175.	1151.	1476.	1202.	1290.	1134.	1110.
Final effluent, lbs/day	178.	152.	143.	148.	150.	164.	167.	312.	168.	192.	150.	155.
Removal across primary, %	18.	20.	42.	39.	23.	26.	26.	31.	27.	27.	30.	30.
Removal across plant, %	86.	90.	90.	90.	90.	89.	89.	86.	90.	89.	91.	90.
Lbs COD/day/lbs aerat. solids	.31	.43	.39	.39	.38	.35	.44	.61	.32	.37	.43	.43
Nitrogen												
Total nitrogen, raw influent, mg/l	27.0	29.1	29.7	27.8	31.6	29.9	36.7	30.7	33.3	32.0	29.0	32.4
Kjldl, final effluent, mg/l****	2.1	1.8	3.3	3.0	2.0	2.1	2.9	4.9	2.8	2.8	2.1	2.1
NO_3-N, final effluent, mg/l	10.8	12.2	4.6	5.8	13.1	10.6	14.7	10.9	11.5	10.8	15.8	13.0
Total N, final effluent, mg/l	12.9	14.0	7.9	8.8	14.1	12.7	17.6	15.8	14.3	13.6	17.9	15.1
Removal, Total N, mg/l	14.1	15.1	21.8	19.0	17.5	17.2	19.1	14.9	19.0	18.4	11.1	17.3
Removal, Total N, %	52.	52.	73.	68.	56.	58.	52.	49.	57.	57.	38.	53.

* Two-level dosing rate, Sept. 3-23
** Averages weighted according to flow
*** Polyelectrolyte dosing to aeration effluent
**** Including ammonia

TABLE XII.— ALUMINUM CHLORIDE TO RAW INFLUENT AND TO PRIMARY EFFLUENT
Effectiveness at Various Mol Doses Al/P

Period 1969	Days	Average of Daily Values for Respective Periods Phosphorus mg/l P Total Raw	Total F. Effl	Sol F. Effl	Dose Al/P	Rmvd P %	Insolubilized %	EMRr	EMRi
			Aluminum CHloride to Raw Influent						
Aug. 24-27	5	11.2	3.6	3.4	1.25	68.	70.	1.84	1.78
	6	12.5	3.3	2.9	1.79	74.	77.	2.42	2.32
Aug. 28-Sept. 2	6	9.7	2.8	2.4	1.82	71.	75.	2.56	2.43
Aug. 28-Sept. 2 wt. av.**	6	9.0	2.8	2.4	2.04	69.	71.	3.13	2.87
			Aluminum Chloride to Primary Effluent						
Sept. 9-13*	5	13.5	2.6	2.2	1.65	81.	84.	2.04	1.97
Sept. 14-18*	5	12.9	2.3	1.7	2.02	82.	87.	2.46	2.32
Sept. 19-23*	5	14.0	2.8	1.1	2.41	80.	92.	3.01	2.62
Sept. 24-Oct. 1	8	14.0	2.8	1.1	2.41	80.	92.	3.01	2.62
Oct. 2-6	5	15.9	2.9	1.3	2.20	82.	92.	2.68	2.39
Oct. 11-15	5	13.7	4.3	1.1	2.21	68.	92.	3.25	2.40
			Polyelectrolyte to Aeration Effluent						
Oct. 7-10	4	11.9	1.1	1.0	2.55	91.	92.	1.80	2.77
Oct. 7-10 wt. av.**	4	11.5	1.2	.9	2.56	91.	92.	2.81	2.78

*Periods of Sept. 2-23, diurnal dose rate at two-level. All other periods, one-level rate.
**Averages weighted according to flow.

TABLE XIII. – SLUDGE PRODUCTION
Without, and with Iron and Aluminum

Column No.	1	2	3
Period	7/20-28/69	6/8-13/69	9/9-13/69
Flow, MGD	.52	.78	.49
COD load, lbs/day	1214.	1600.	1555.
Phosphorus load, lbs/day as P	53.4	54.7	55.2
Phosphorus load, lbs/day as PO_4	164.	168.	169.
Cationic treatment	none	Fe (II)	Al (III)
Point of injection	-	Raw infl.	Prim effl.
Dose, mol ratio, Fe/P or Al/P	0	1.31	1.65
Dose, lbs/day as Fe or Al	0	129.	79.
Phosphorus removed, %	12.	83.	81.
Phosphorus removed, lbs/day as PO_4	20.	140.	137.
Sludge to digester, primary + waste, gal/day	5350.	4679.	6292.
Solids in sludge, dry wt., %	1.44	2.24	1.72
Solids to digester, lbs/day	644.	872.	900.
% ash in solids	26.	50.	38.
Phosphorus entering sludge, lbs/day as PO_4			
Biological uptake, assumed	20.	(20)	(20)
From Fe or Al precipitation	-	120.	117.
Total	20.	140.	137.
Fe or Al entering sludge from dose, lbs/day			
Dose minus Fe or Al in plant effluent	0	126.	77.
Fe or Al plus PO_4 entering sludge, lbs/day	-	246.	194.
Calculated quantity of precipitants from Fe or Al dose, lbs/day*			
PO_4 to equiv. $FePO_4$ or $AlPO_4$	-	191.	150.
Remaining Fe and Al to $Fe(OH)_3$ and $Al(OH)_3$	-	105.	127.
Total	-	296.	277.
Calculated solids non-attributed to Fe or Al precipitants, lbs/day			
Sludge solids minus calculated precipitants	-	576.	623.
Probable solids content of digested sludge, % **	5.5	5.5	2.5
Probable % ash in solids**	60.	65.	55.

*Arbitrary, to estimate at least the minimum of dry weight solids from the iron and aluminum doses through hydrolysis and phosphate uptake. Aquo ligands are not accounted for.

**Based respectively on analyses of samples of digested sludge drawings before the use of iron or aluminum, prior to January 20, 1968; 2 to 5 months after initiation of iron treatment; and 1 to 3 months after initiating aluminum treatment.

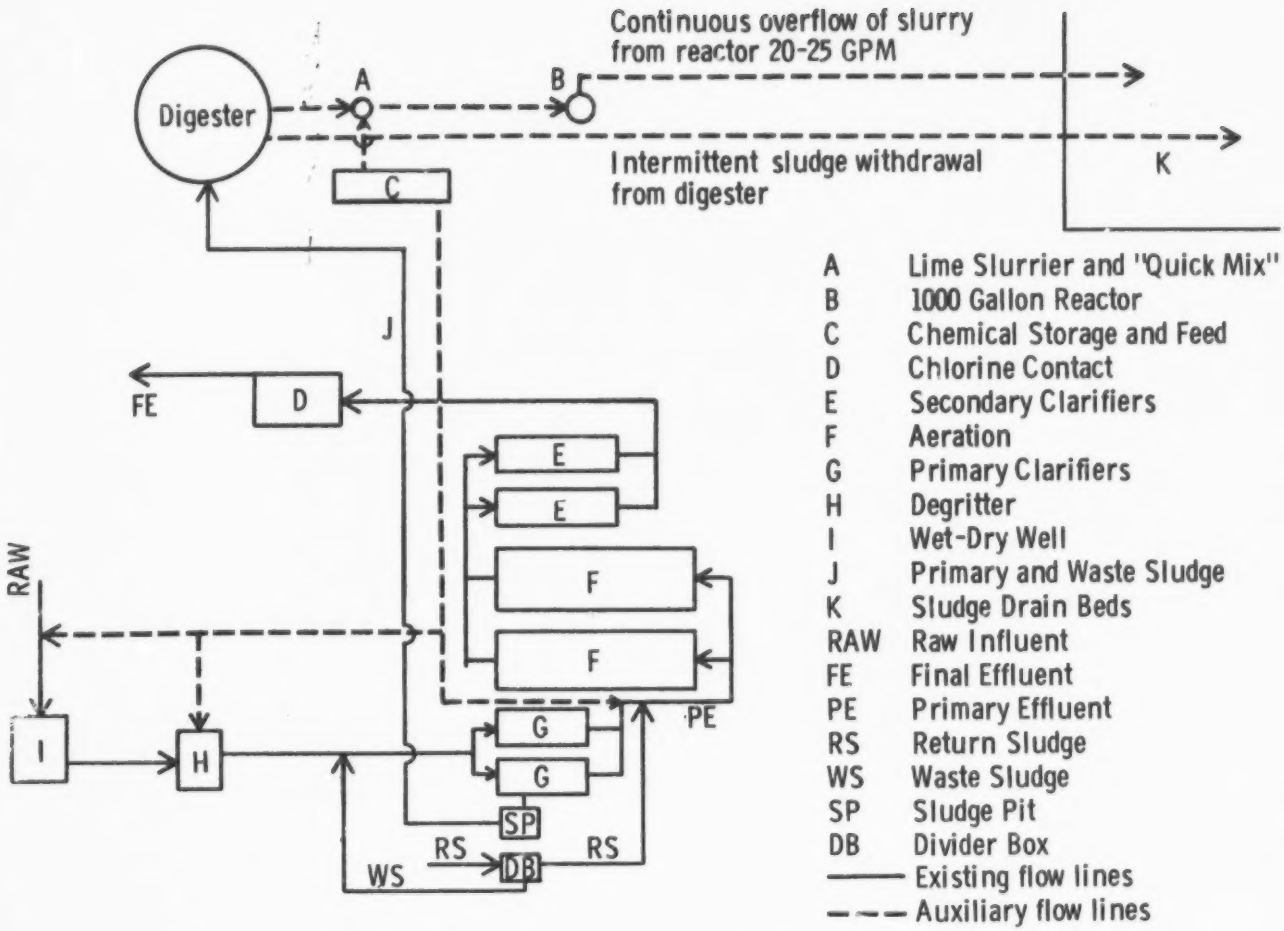

Figure 1.— Plant layout and flow schematic for phosphorus removal processes, Texas City, Plant No. 2

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Figure 1a.-Lime-phosphate sludge on the drain bed, from treatment of digester liquor after drying to 20-30% moisture content.

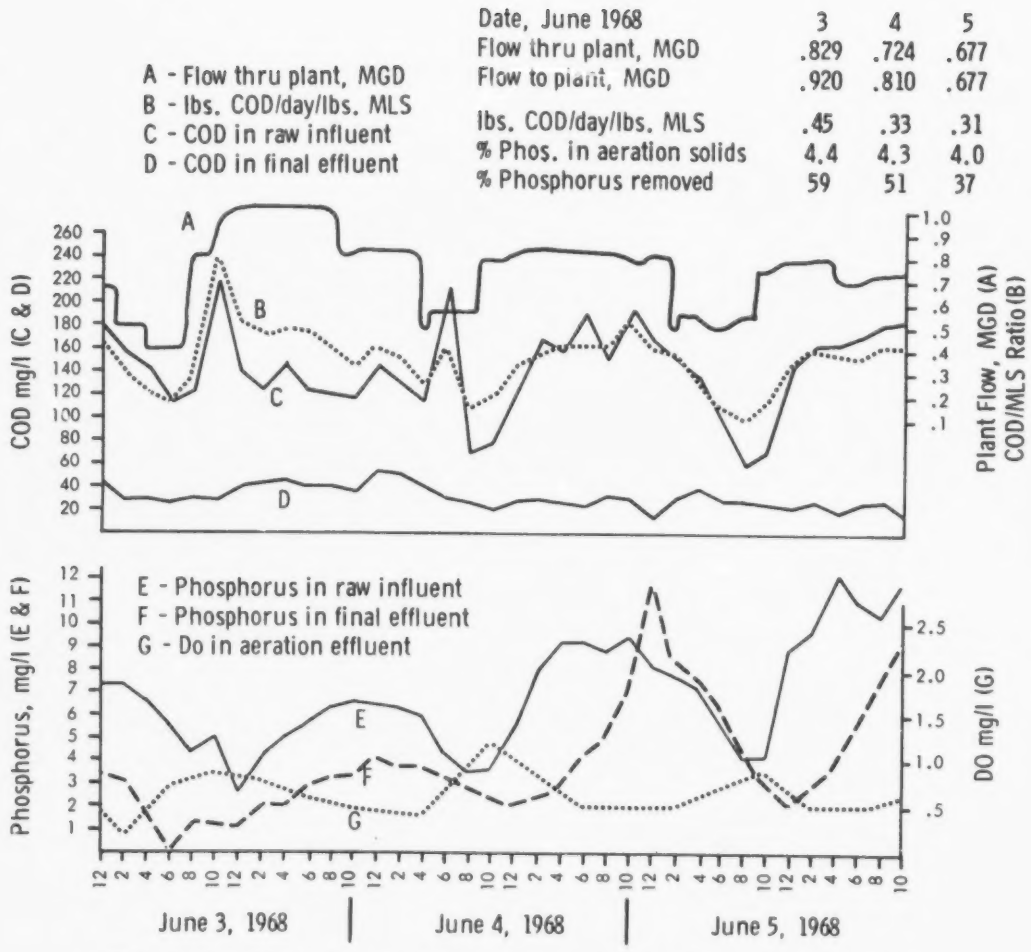
A - Flow thru plant, MGD
B - lbs. COD/day/lbs. MLS
C - COD in raw influent
D - COD in final effluent
Date, June 1968 3 4 5
Flow thru plant, MGD .829 .724 .677
Flow to plant, MGD .920 .810 .677
lbs. COD/day/lbs. MLS .45 .33 .31
% Phos. in aeration solids 4.4 4.3 4.0
% Phosphorus removed 59 51 37
COD mg/l (C & D)
Plant Flow, MGD (A)
COD/MLS Ratio (B)
E - Phosphorus in raw influent
F - Phosphorus in final effluent
G - Do in aeration effluent
Phosphorus, mg/l (E & F)
DO mg/l (G)
June 3, 1968
June 4, 1968
June 5, 1968

Figure 2._ Bi-hourly variations of plant influent and effluent phosphorus and COD, aeration effluent DO, plant flow rate, and COD/MLS ratio, daily variations of other parameter. No cations added to primary or aeration processes.

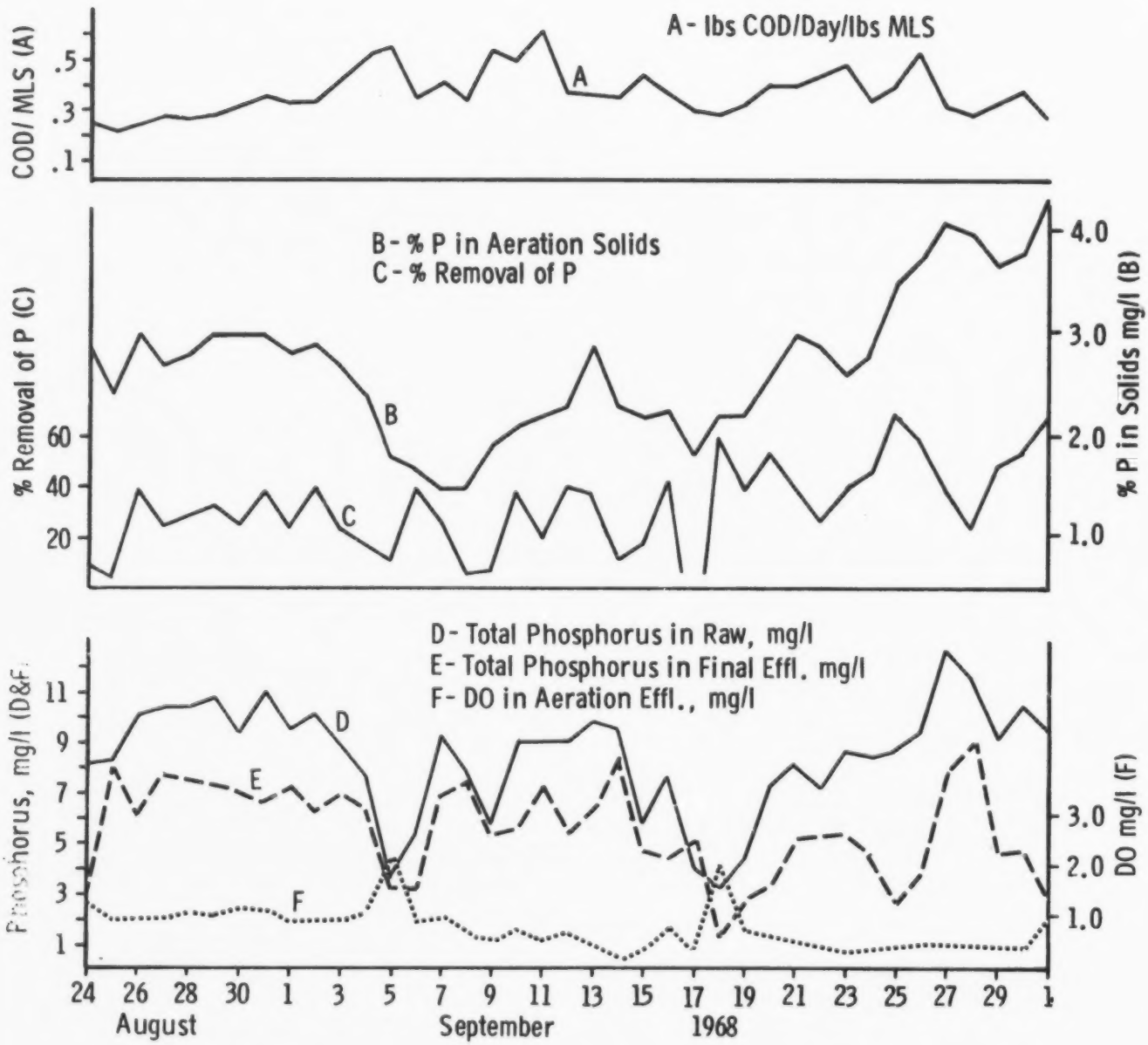

Figure 3._ Daily variations of phosphorus removal, COD/MLS loading, %phosphorus in aeration solids and DO in aeration effluent; dry and wet weather flow; Aug. 24 - Oct. 1, 1968; no added cations to primary or aeration processes.

Date Aug. 1968	13	14	15	16	17	18
Flow to Plant, MGD	.479	.475	.475	.490	.456	.474
Flow thru Plant, MGD	.419	.385	.355	.390	.376	.394
lbs. COD/day/lbs. MLS	.52	.26	.26	.39	.35	.37
% P in Aeration Solids	3.2	3.1	3.8	4.1	3.4	4.0
% Phosphorus Removed	34.	53.	51.	53.	48.	35.

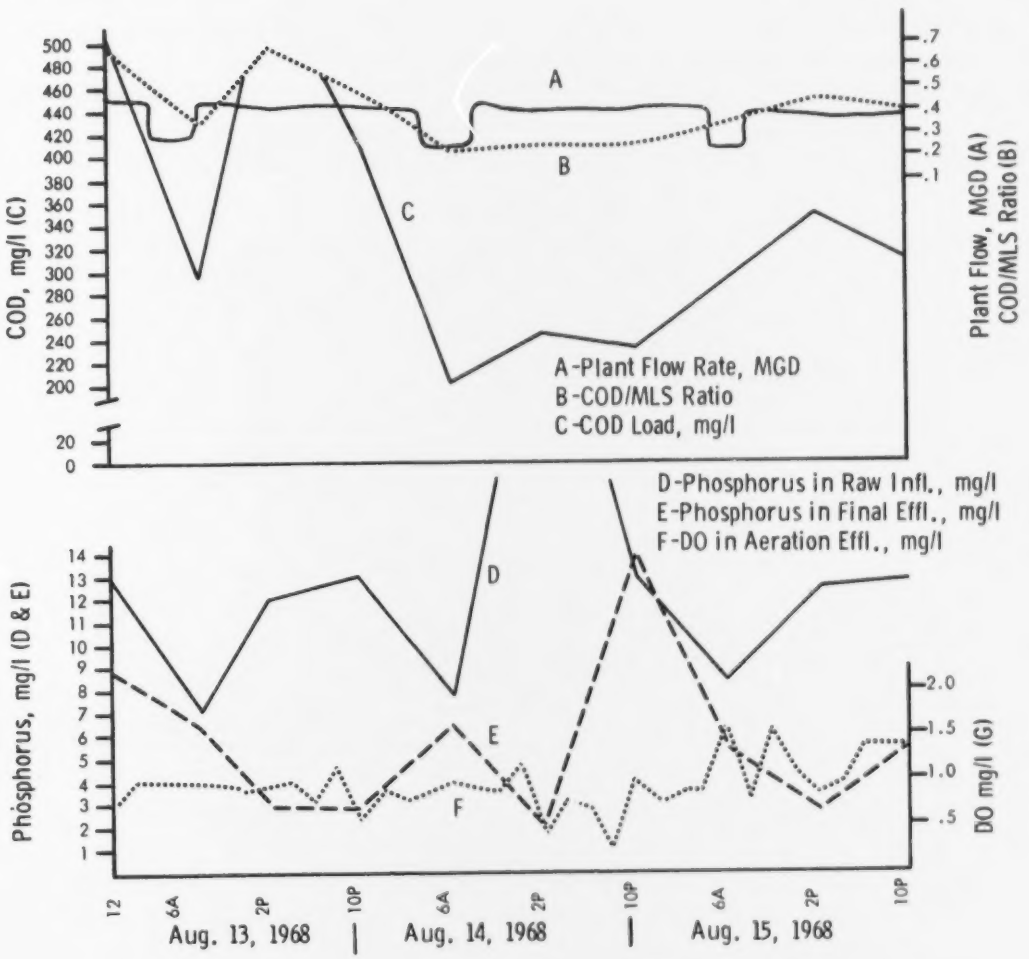

Figure 3a.— Diurnal variations of flow rates, COD/MLS ratio, influent COD, influent and effluent phosphorus, aeration effluent DO, % P in aeration solids, and % phosphorus removed Aug. 13-15, 1968; No cations added to primary or aeration processes.

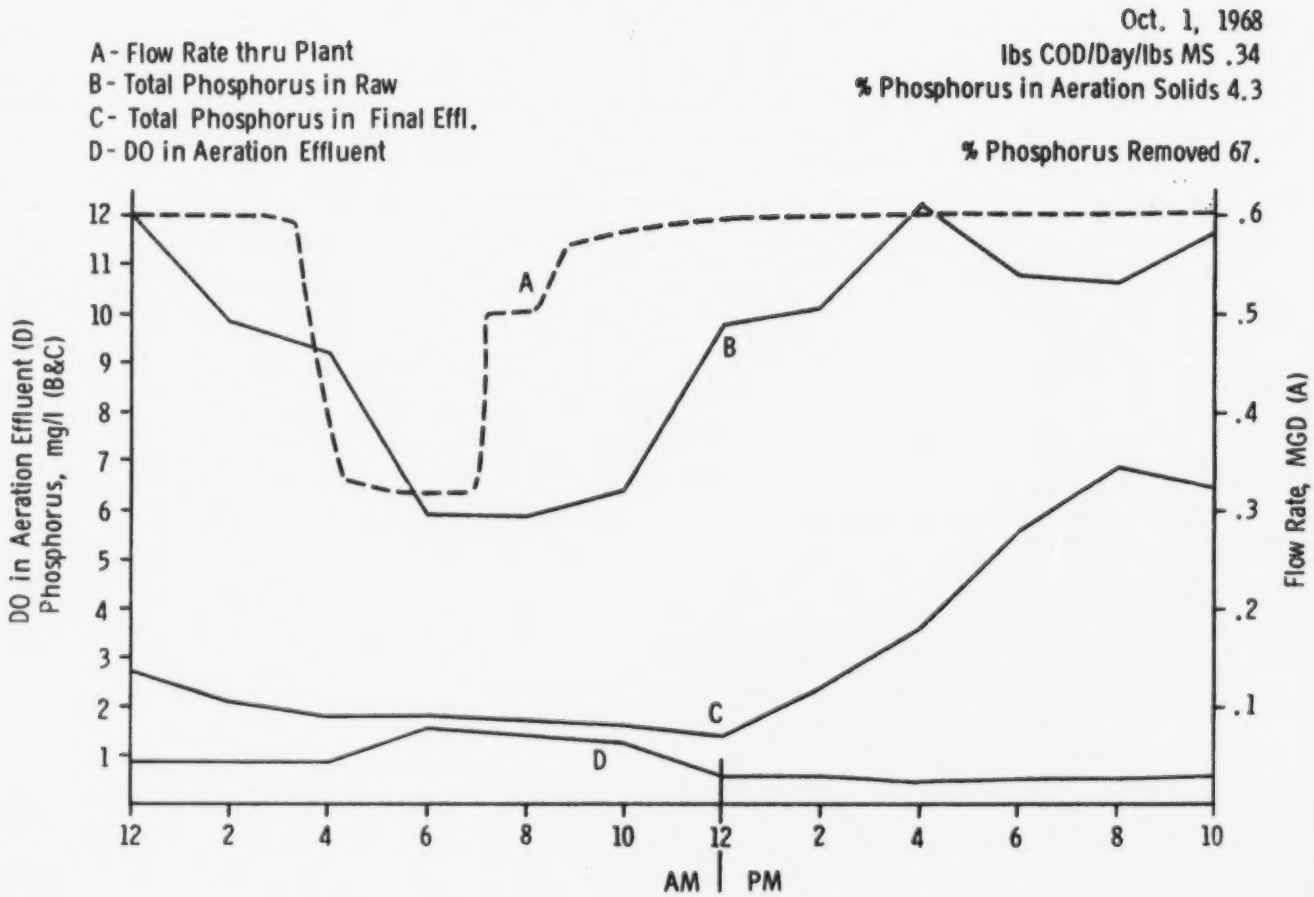

Figure 4._ Around-the-clock variations of plant flow, influent and effluent phosphorus, and aeration effluent dissolved oxygen, Oct. 1, 1968

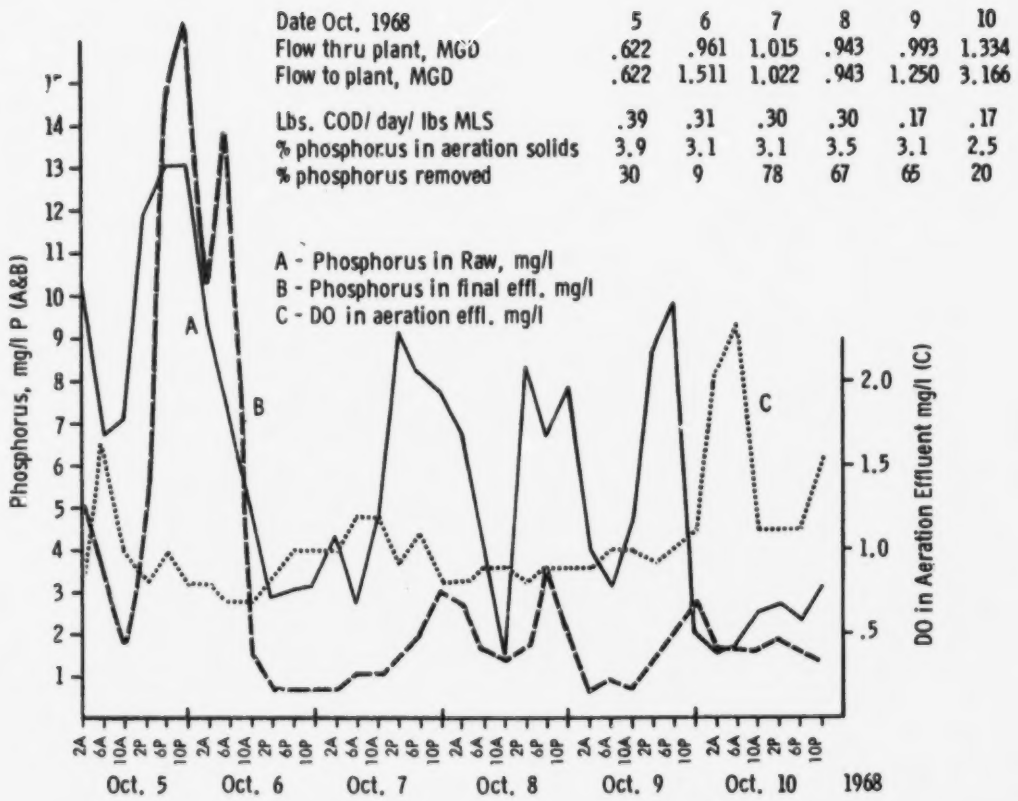
Date Oct. 1968 5 6 7 8 9 10
Flow thru plant, MGD .622 .961 1.015 .943 .993 1.334
Flow to plant, MGD .622 1.511 1.022 .943 1.250 3.166
Lbs. COD/ day/ lbs MLS .39 .31 .30 .30 .17 .17
% phosphorus in aeration solids 3.9 3.1 3.1 3.5 3.1 2.5
% phosphorus removed 30 9 78 67 65 20
A - Phosphorus in Raw, mg/l
B - Phosphorus in final effl. mg/l
C - DO in aeration effl. mg/l
Phosphorus, mg/l P (A&B)
DO in Aeration Effluent mg/l (C)
Oct. 5
Oct. 6
Oct. 7
Oct. 8
Oct. 9
Oct. 10
1968

Figure 5.— Four-hour to daily variations of influent and effluent phosphorus, and of other parameters, Oct. 5-10 1968, spanning a 3-day period of maximum removal observed, average of 70%; no cations added to primary or aeration processes.

Date November 1968	18	19	20
Flow thru plant, MGD	.689	.622	.646
Flow to plant, MGD	.790	.673	.740
Lbs. COD/day/lbs. MLS	.41	.34	.38
% phosphorus in aeration solids	1.9	1.7	1.7
% phosphorus removed	24	10	12

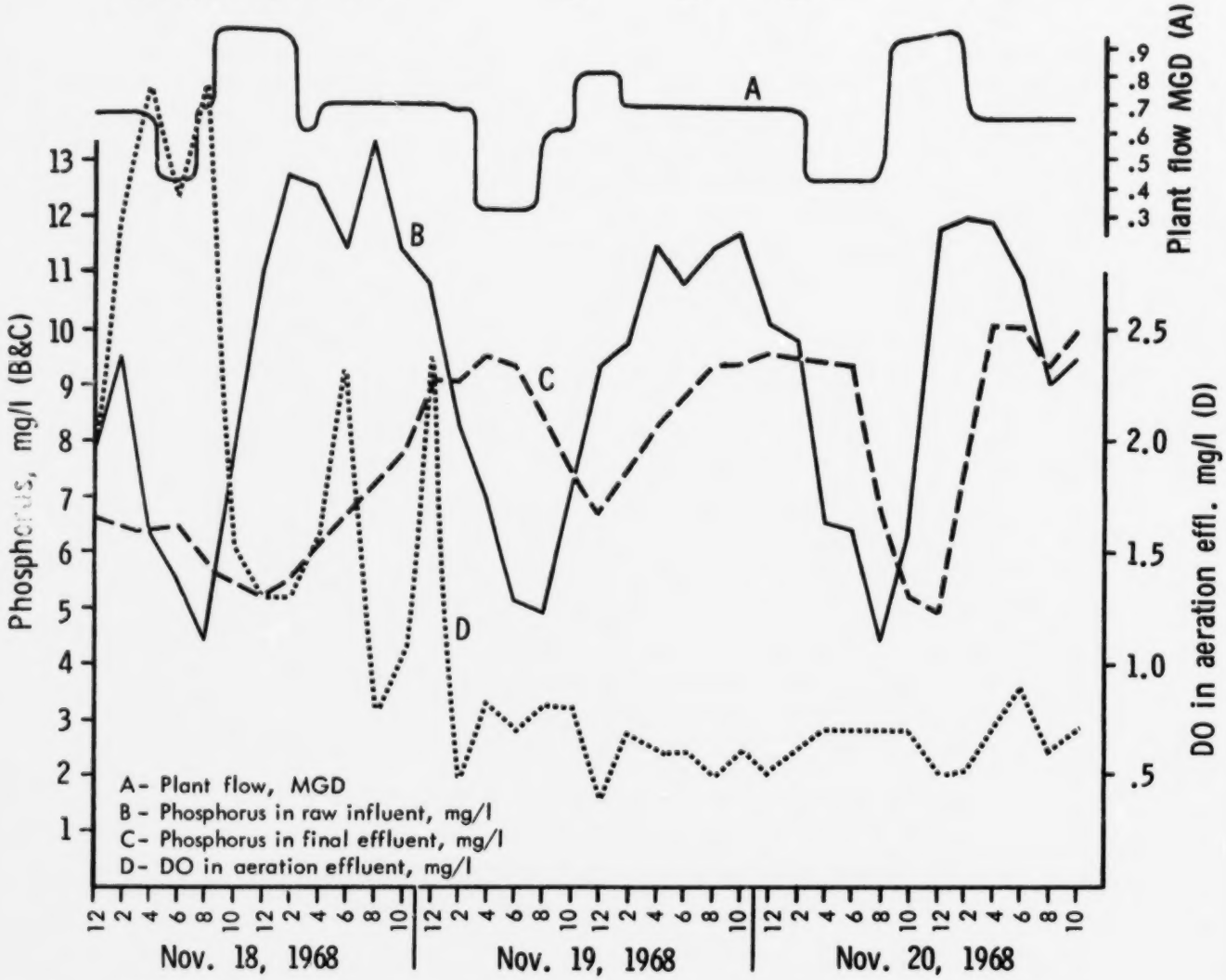

Figure 6._ Bi-hourly variations of plant influent and effluent phosphorus and aeration effluent DO, and daily variations of other parameters; Nov. 18-20, 1968, no added cations to primary or aeration processes.

Date November 1968	24	25	26
Flow thru plant, MGD	.666	.656	.646
Flow to plant, MGD	.666	.656	.655
Lbs. COD/day/lbs. MLS	.40	.39	.40
% phosphorus in aeration solids	2.7	2.8	3.0
% phosphorus removed	53	47	41

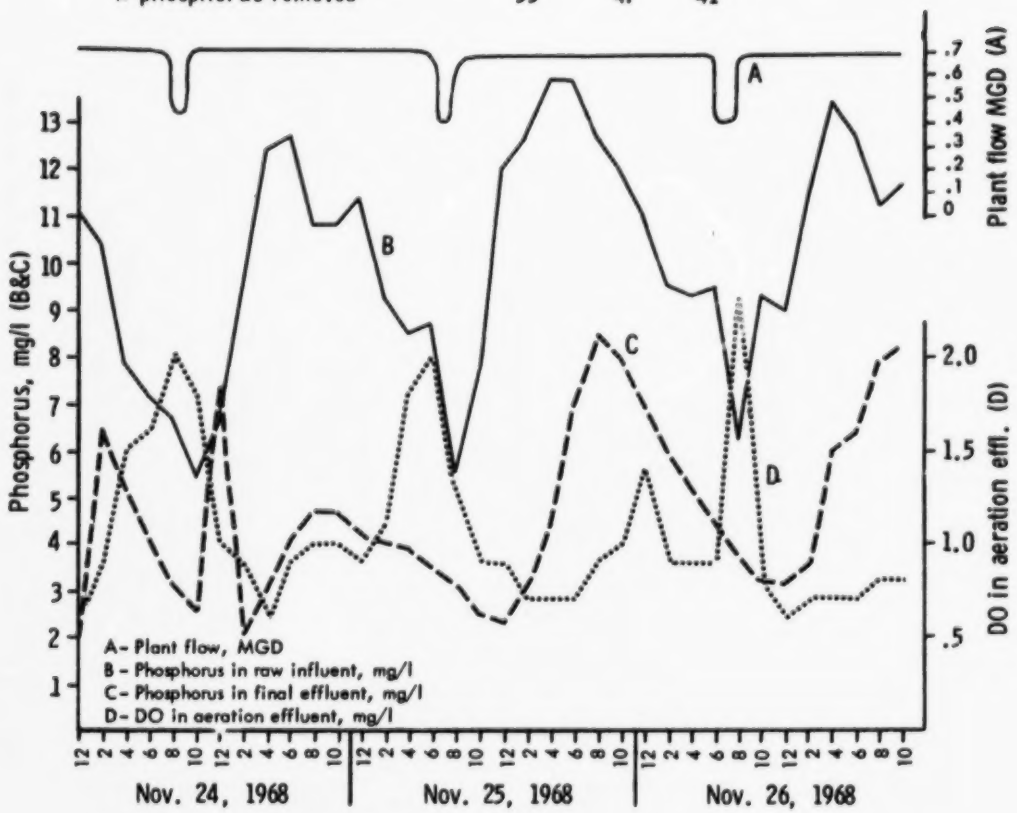

Figure 7.— Bi-hourly variations of plant influent and effluent phosphorus and aeration effluent DO, and daily variations of other parameters; Nov. 24, Nov. 25, & Nov. 26, 1968, no added cations to primary or aeration processes.

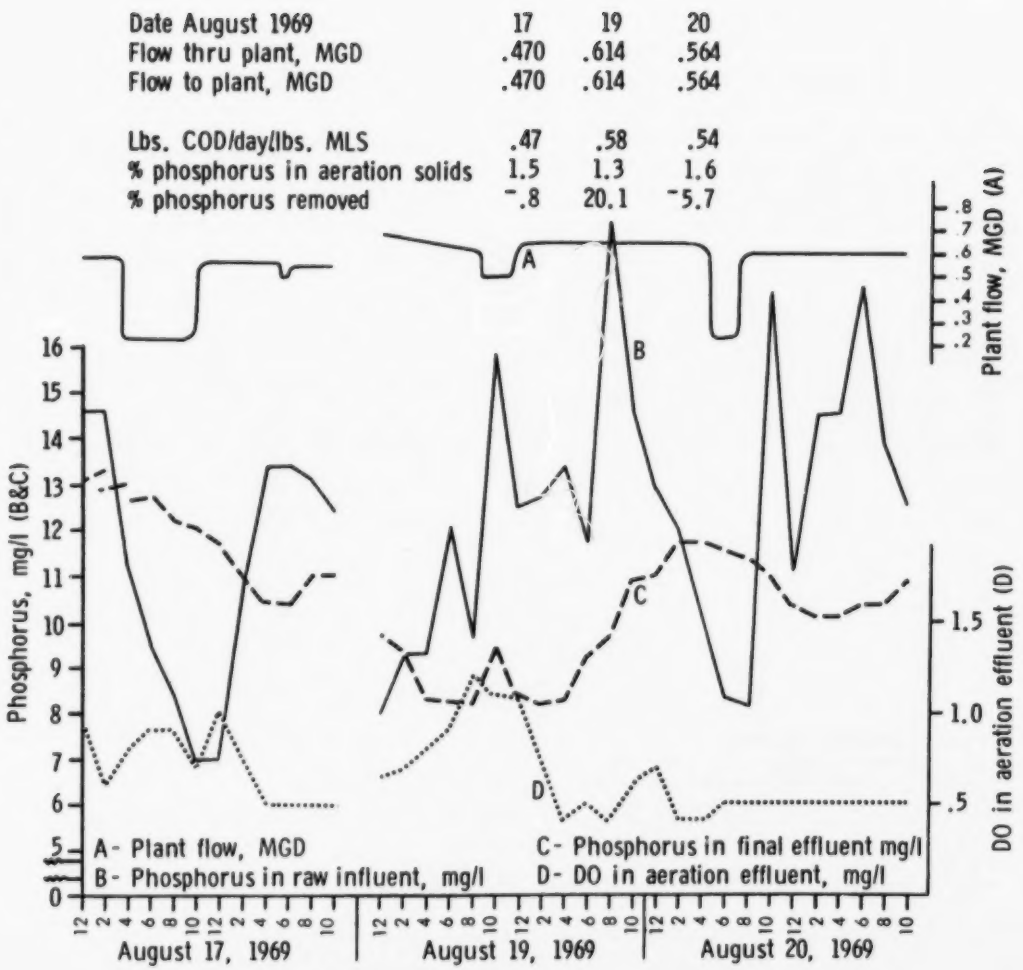
Date August 1969 17 19 20
Flow thru plant, MGD .470 .614 .564
Flow to plant, MGD .470 .614 .564
Lbs. COD/day/lbs. MLS .47 .58 .54
% phosphorus in aeration solids 1.5 1.3 1.6
% phosphorus removed -.8 20.1 -5.7
Phosphorus, mg/l (B&C)
Plant flow, MGD (A)
DO in aeration effluent (D)
A- Plant flow, MGD
B- Phosphorus in raw influent, mg/l
C- Phosphorus in final effluent mg/l
D- DO in aeration effluent, mg/l
August 17, 1969
August 19, 1969
August 20, 1969

Figure 8.— Bi-hourly variations of plant influent and effluent phosphorus and aeration effluent DO, and daily variations of other parameters, Aug. 17, Aug. 19, & Aug. 20, 1969, no added cations to primary or aeration processes.

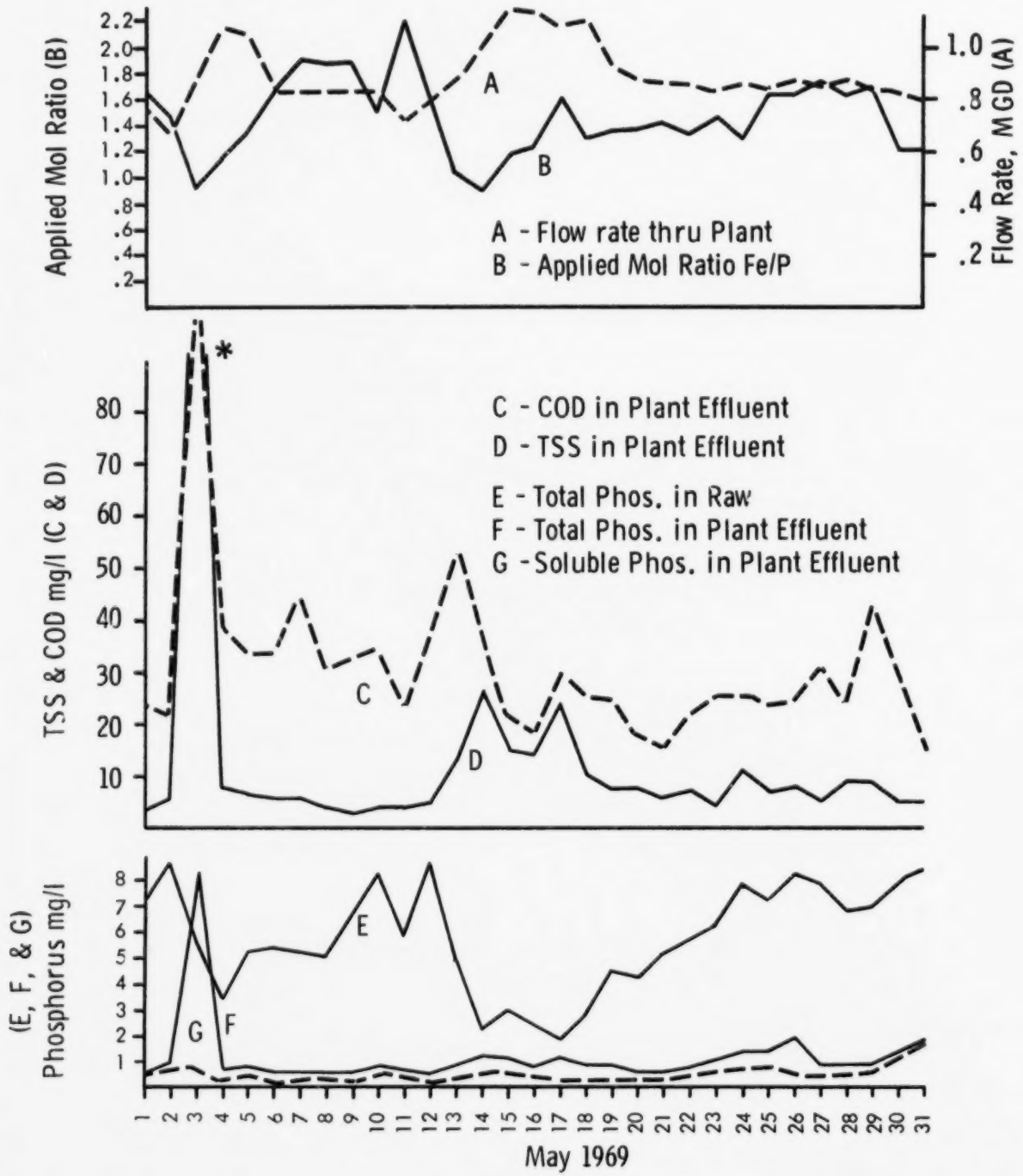
Applied Mol Ratio (B)
Flow Rate, MGD (A)
A - Flow rate thru Plant
B - Applied Mol Ratio Fe/P
TSS & COD mg/l (C & D)
C - COD in Plant Effluent
D - TSS in Plant Effluent
E - Total Phos. in Raw
F - Total Phos. in Plant Effluent
G - Soluble Phos. in Plant Effluent
(E, F, & G) Phosphorus mg/l
May 1969

Figure 9._ Ferrous iron injection to raw influent, Texas City Plant No. 2 May 1969 *(on May 3 inadvertant acceptance of 1.5-1.6 MGD rate for 2-3 hours, raised effluent COD, suspended solids and phosphorus for the day to 108, 141, and 8.3 mg/l respectively.)

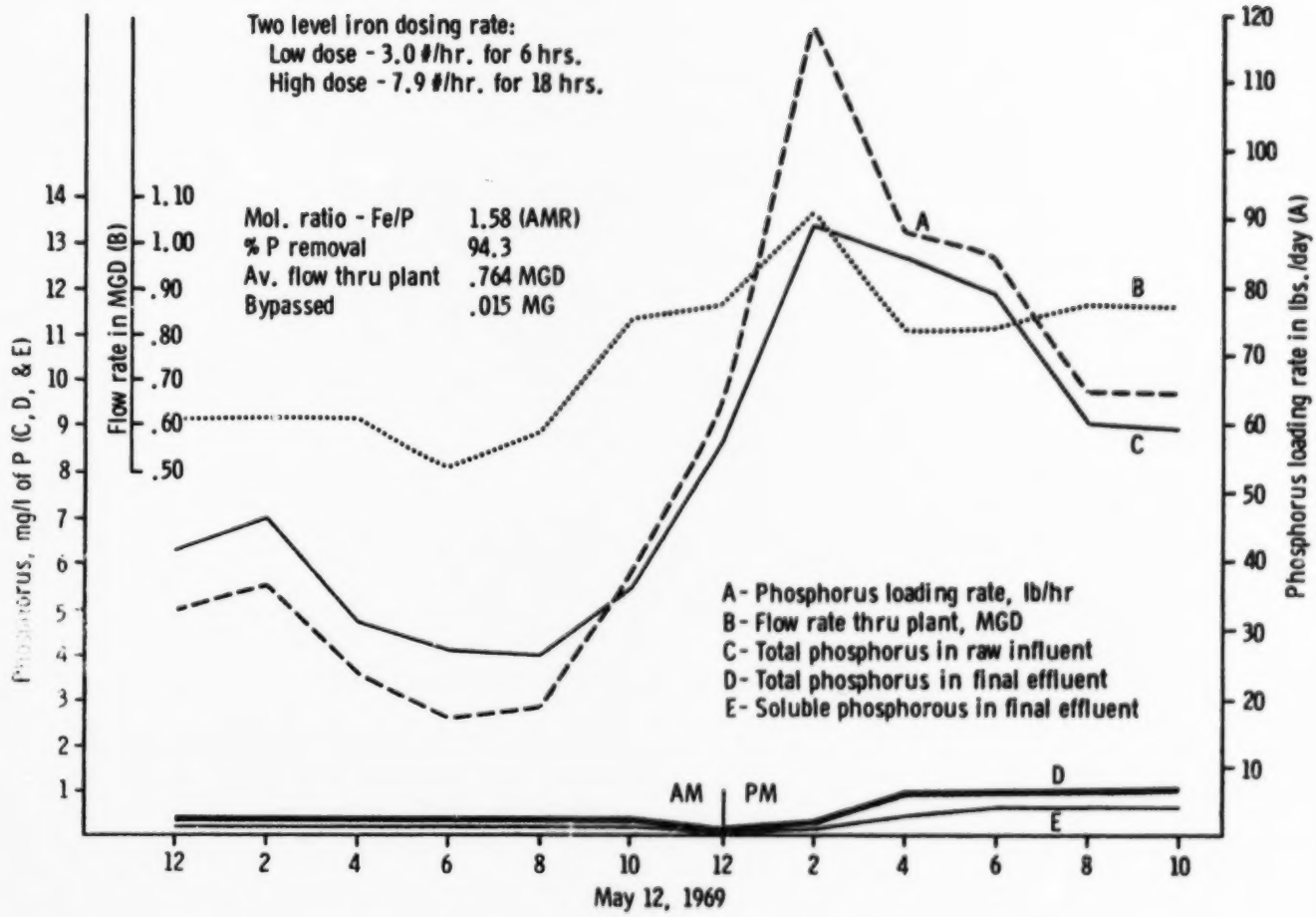
Two level iron dosing rate:
Low dose - 3.0 #/hr. for 6 hrs.
High dose - 7.9 #/hr. for 18 hrs.
Mol. ratio - Fe/P 1.58 (AMR)
% P removal 94.3
Av. flow thru plant .764 MGD
Bypassed .015 MG
A- Phosphorus loading rate, lb/hr
B- Flow rate thru plant, MGD
C- Total phosphorus in raw influent
D- Total phosphorus in final effluent
E- Soluble phosphorous in final effluent
Flow rate in MGD (B)
Phosphorus loading rate in lbs./day (A)
AM
PM
May 12, 1969

Figure 10._ Ferrous iron injection to raw influent, with two diurnal levels of iron dosing, Texas City Plant No. 2

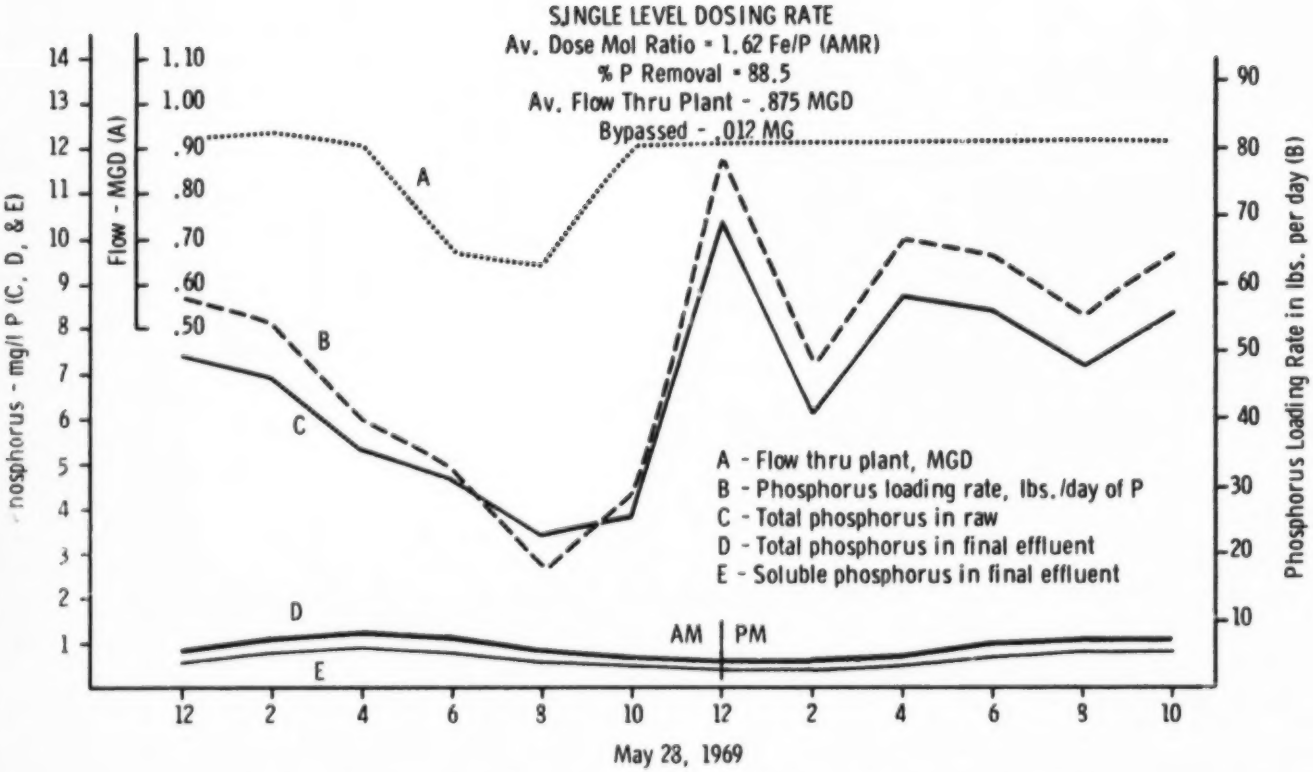

Figure 11._ Ferrous iron injection to raw influent at single level dosing rate, Texas City Plant No. 2

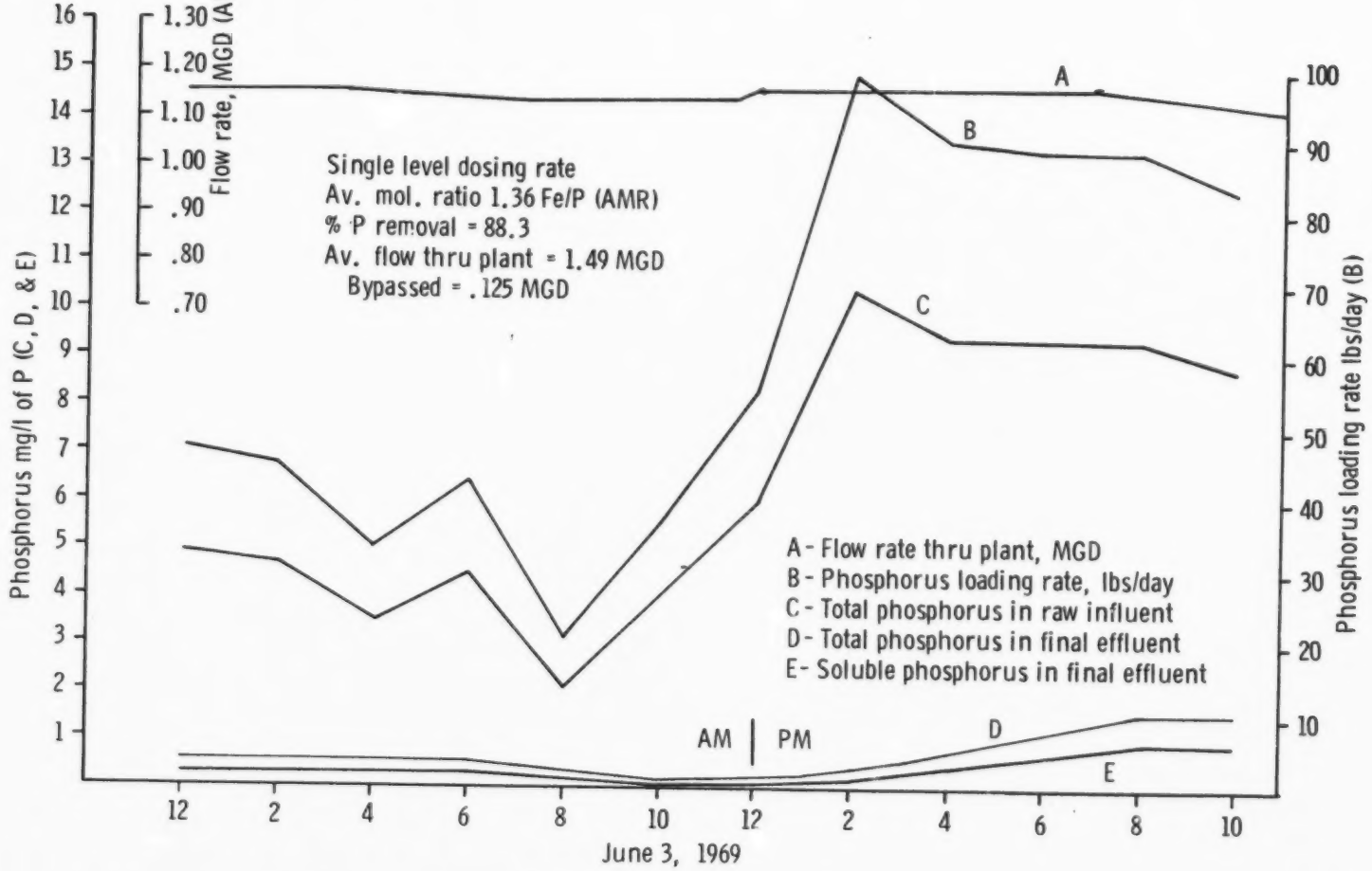
Phosphorus mg/l of P (C, D, & E)
Flow rate, MGD (A)
Phosphorus loading rate lbs/day (B)
Single level dosing rate
Av. mol. ratio 1.36 Fe/P (AMR)
% P removal = 88.3
Av. flow thru plant = 1.49 MGD
Bypassed = .125 MGD
A - Flow rate thru plant, MGD
B - Phosphorus loading rate, lbs/day
C - Total phosphorus in raw influent
D - Total phosphorus in final effluent
E - Soluble phosphorus in final effluent
AM
PM
June 3, 1969

Figure 12._ Ferrous iron injection to raw influent at a single level of dosing rate, Texas City Plant No. 2

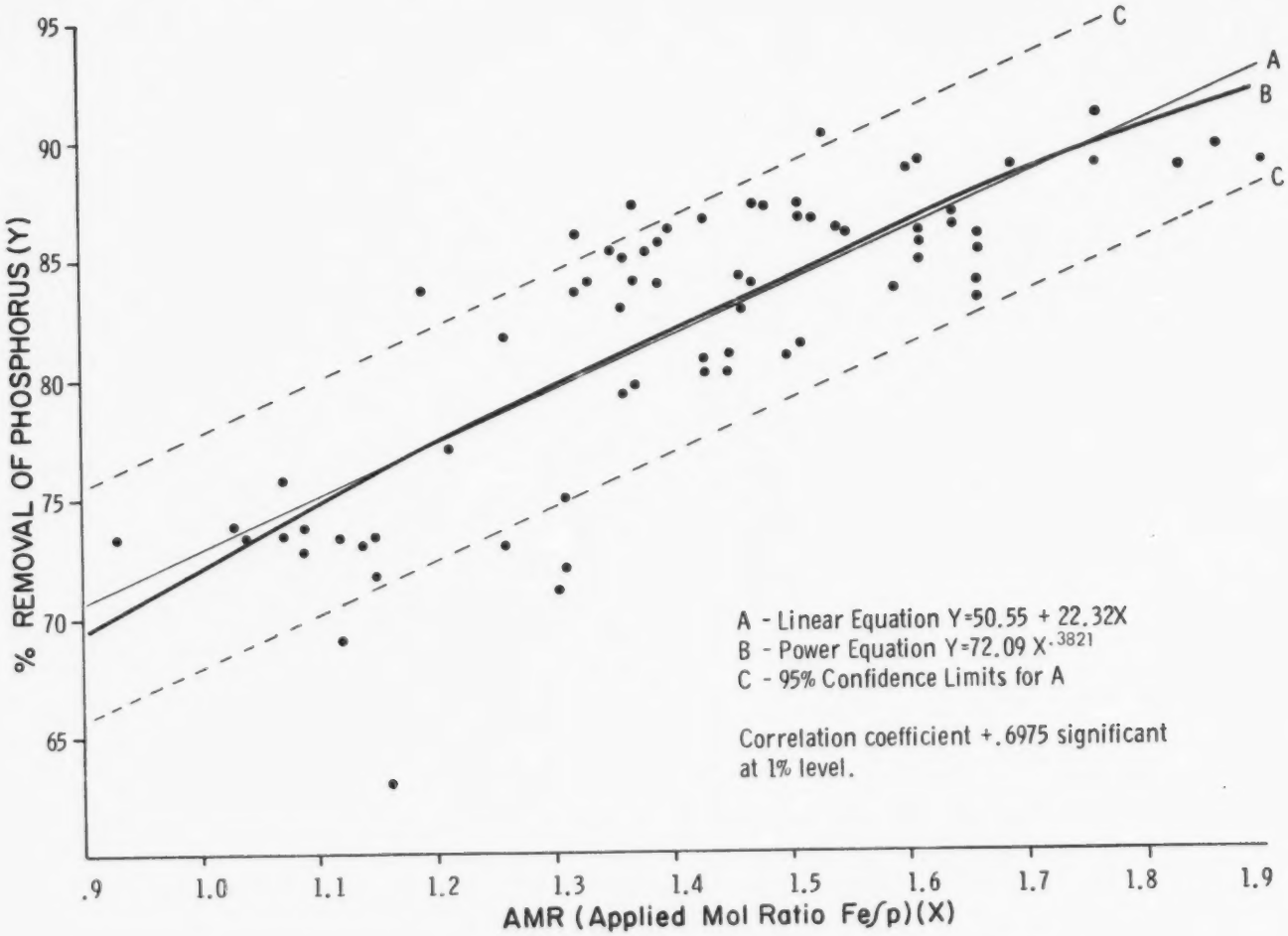

Figure 13a. - Correlation of Applied Mol Ratio (Y) with % Removal of Phosphorus (X). Points are 3-day Moving Averages.

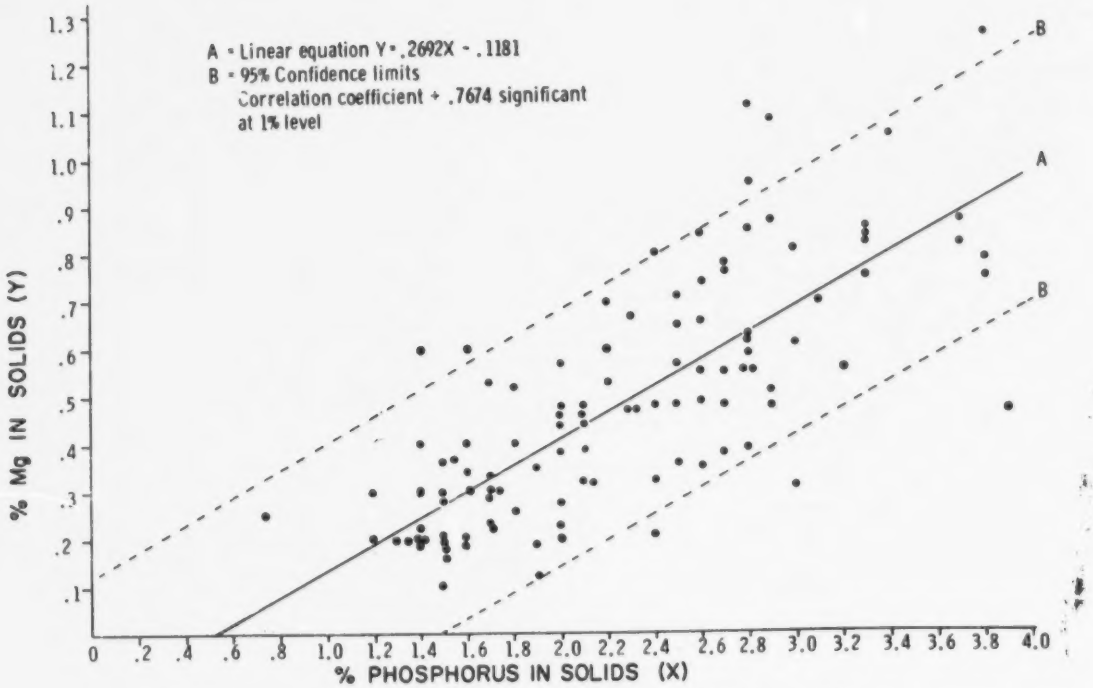
A = Linear equation Y = .2692X - .1181
B = 95% Confidence limits
Correlation coefficient = .7674 significant at 1% level
A
B
B
% Mg IN SOLIDS (Y)
% PHOSPHORUS IN SOLIDS (X)

Figure 13b. - Correlation of % Magnesium (Y) with % Phosphorus (X) in mixed liquor solids.

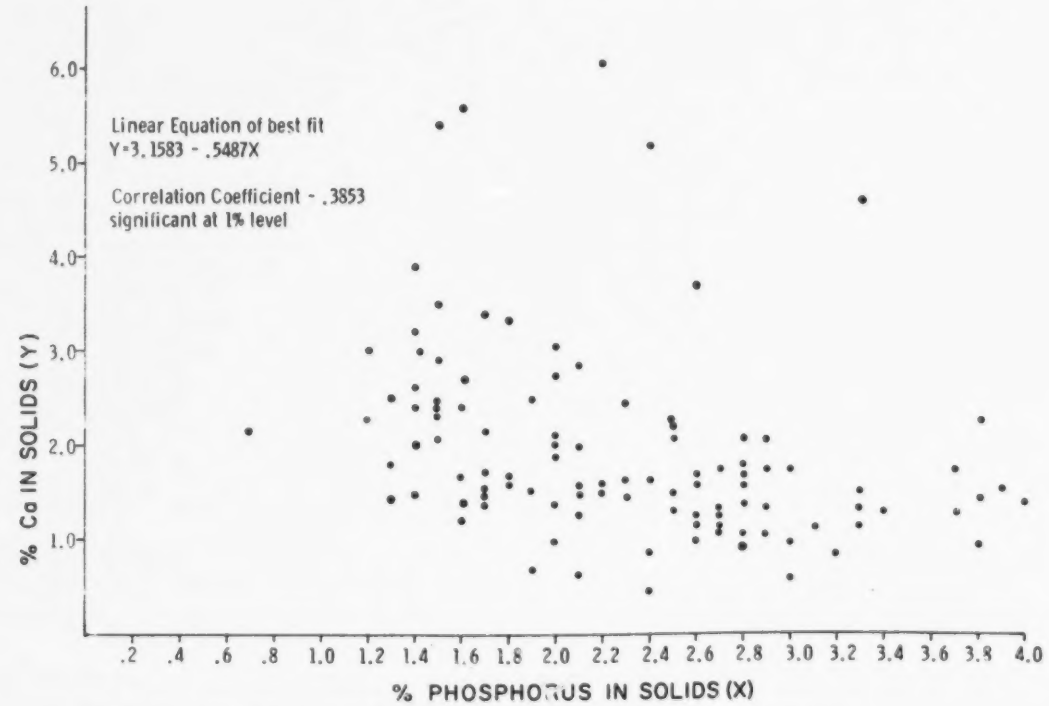
Linear Equation of best fit
Y=3.1583 - .5487X
Correlation Coefficient - .3853
significant at 1% level
% Ca IN SOLIDS (Y)
% PHOSPHORUS IN SOLIDS (X)

Figure 13c. - Scatter Diagram of % Calcium (Y) vs. % Phosphorus (X) in Mixed Liquor Solids.

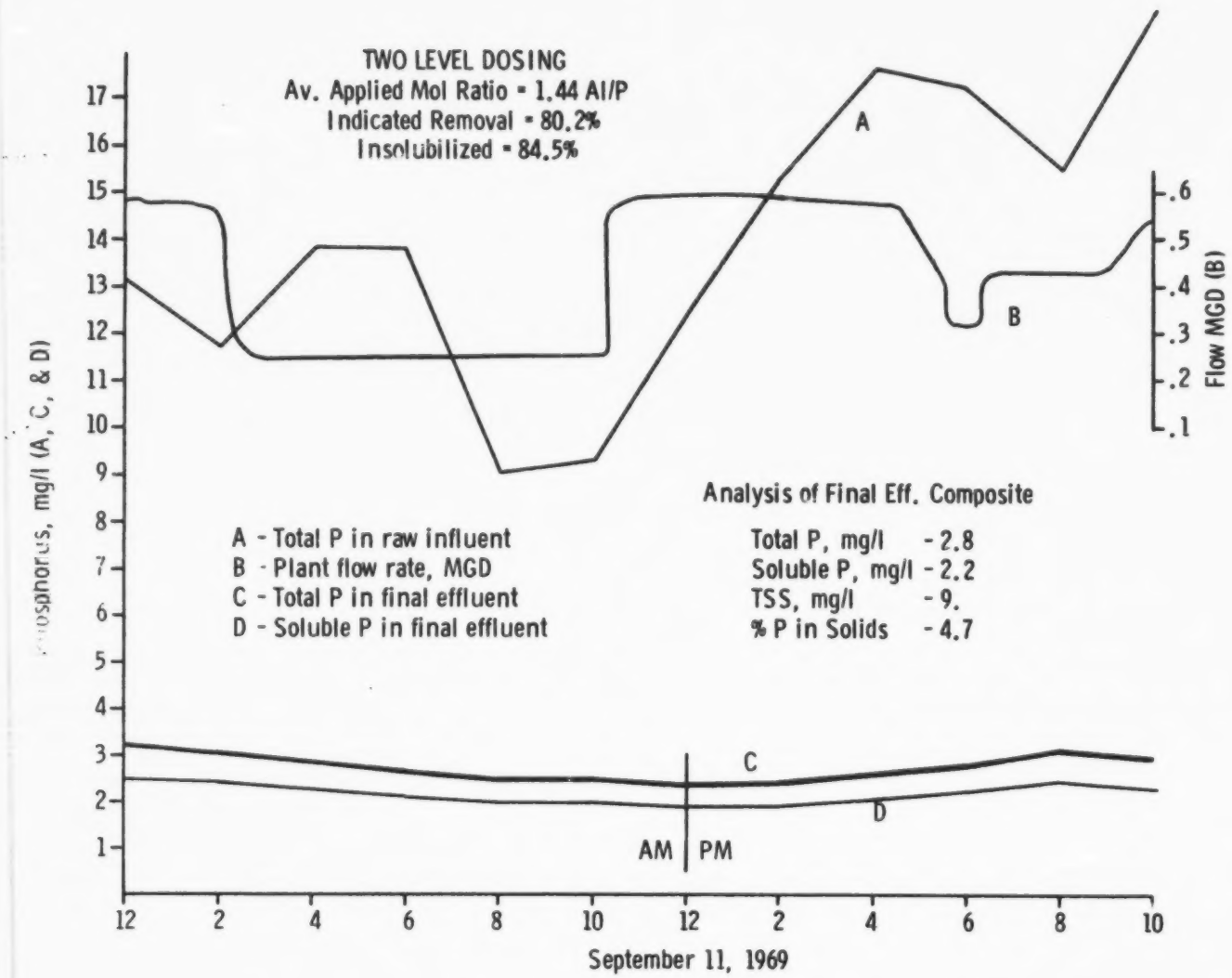
TWO LEVEL DOSING
Av. Applied Mol Ratio = 1.44 Al/P
Indicated Removal = 80.2%
Insolubilized = 84.5%
A
B
C
D
A - Total P in raw influent
B - Plant flow rate, MGD
C - Total P in final effluent
D - Soluble P in final effluent
Analysis of Final Eff. Composite
Total P, mg/l - 2.8
Soluble P, mg/l - 2.2
TSS, mg/l - 9.
% P in Solids - 4.7
Phosphorus, mg/l (A, C, & D)
Flow MGD (B)
AM
PM
September 11, 1969

Figure 14._ Aluminum chloride injection to primary effluent September 11, 1969 Texas City Plant No. 2

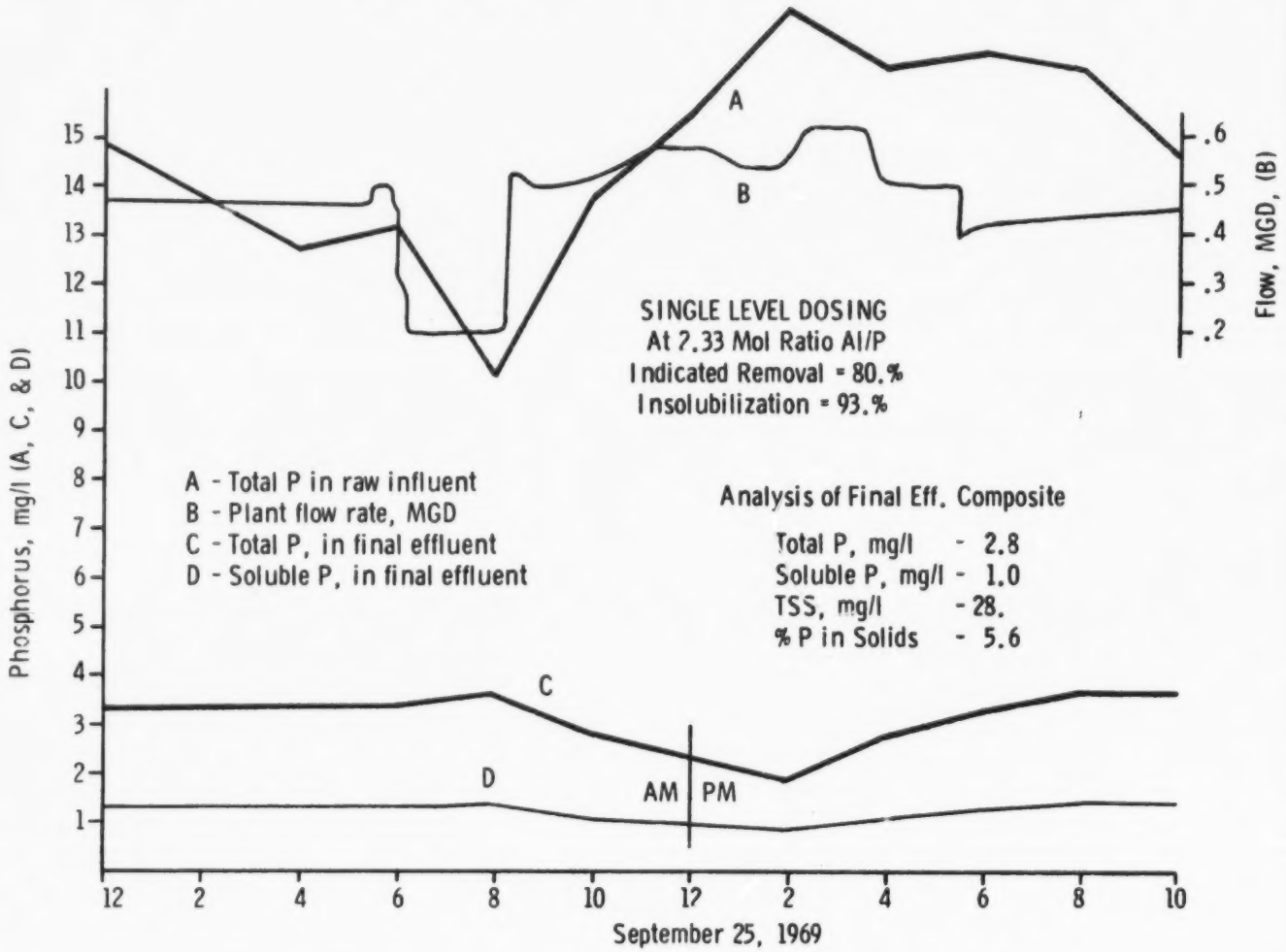

Figure 15._ Aluminum chloride injection to primary effluent September 25, 1969 Texas City Plant No. 2

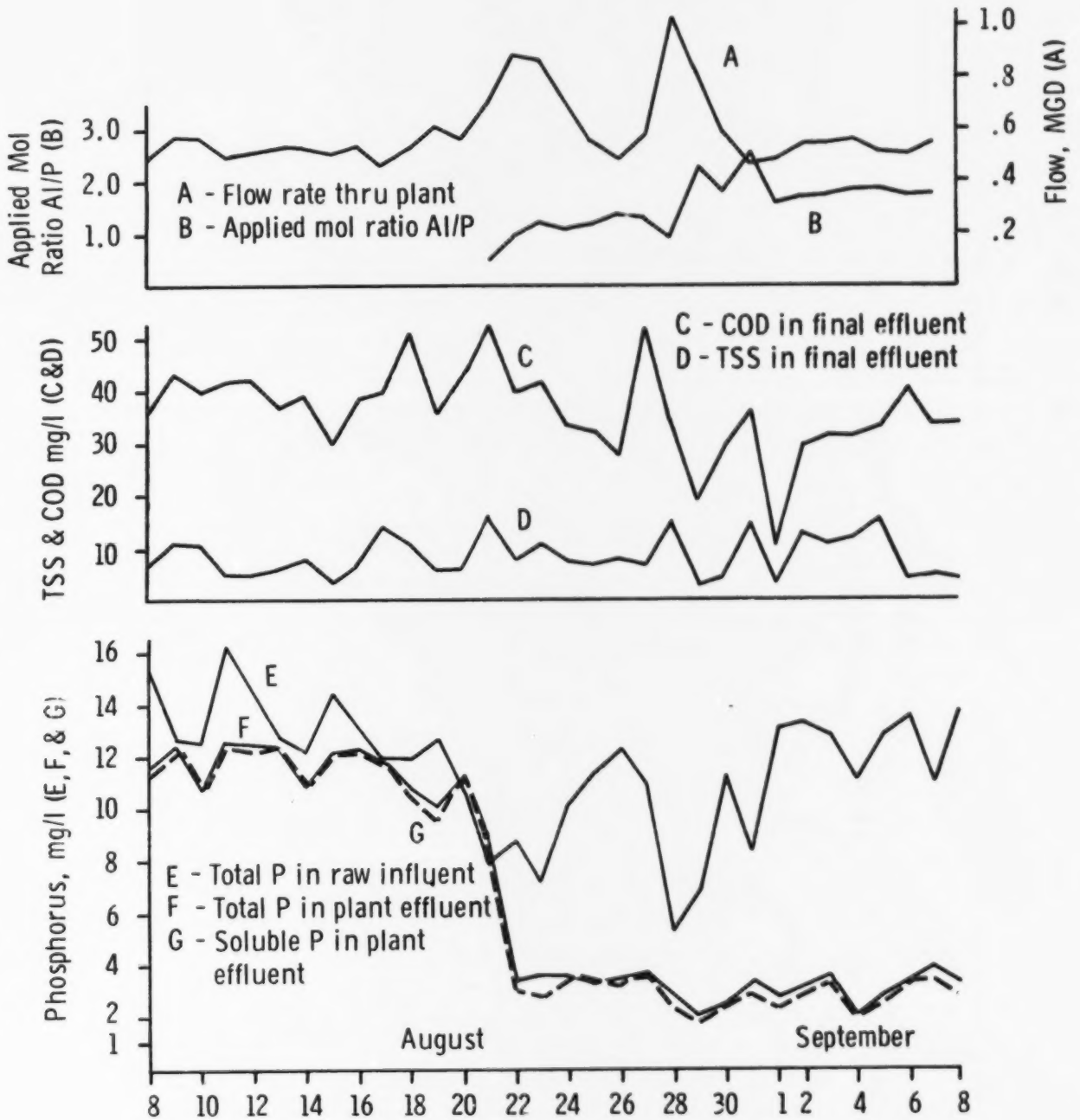

Figure 16._ Aluminum chloride injection into raw influent, August 21-September 8, 1969 Texas City Plant No. 2; no added cations August 8-20.

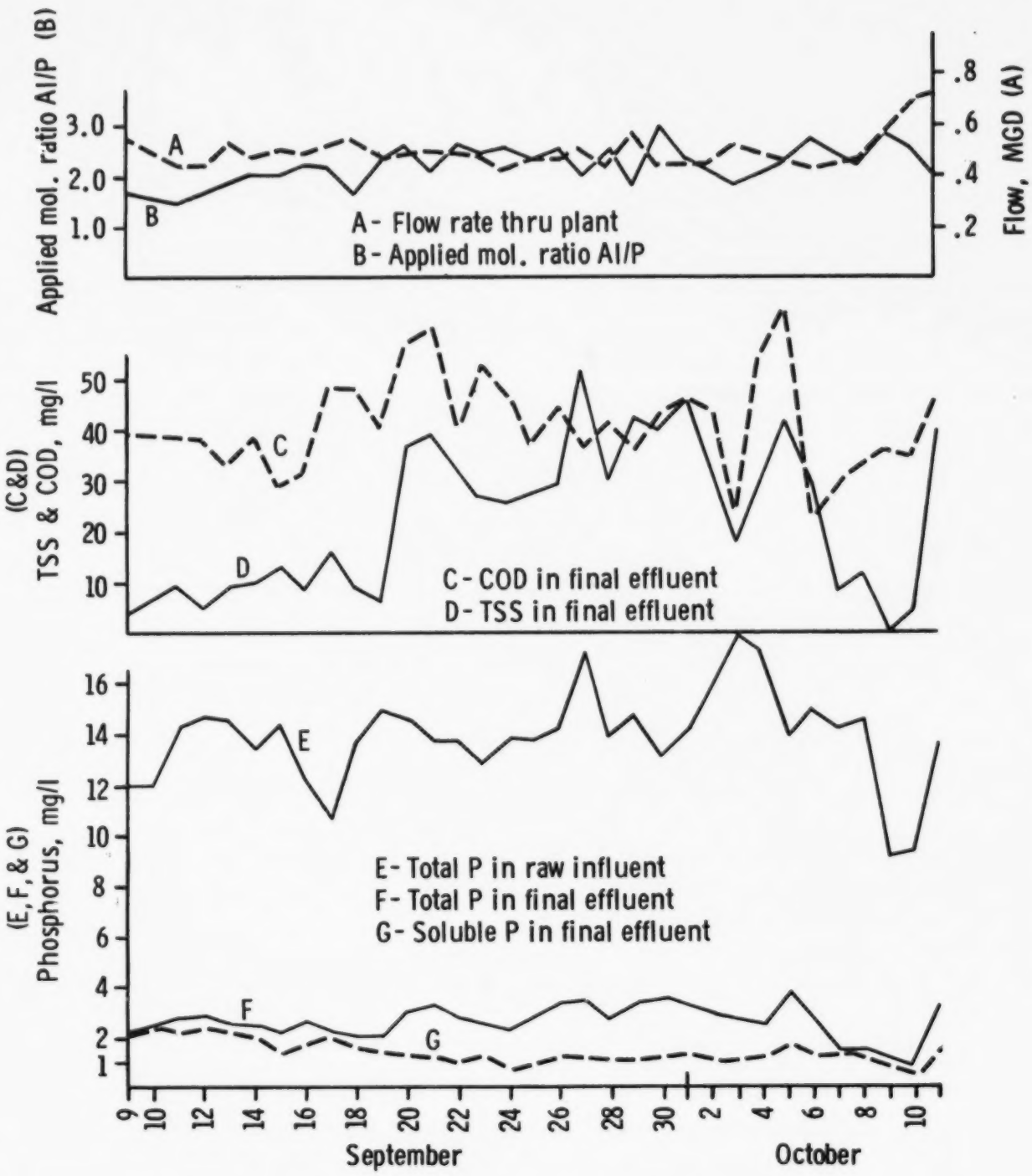

Figure 17._ Aluminum chloride injection into primary effluent Sept. 9-Oct. 11, 1969 Texas City Plant No. 2

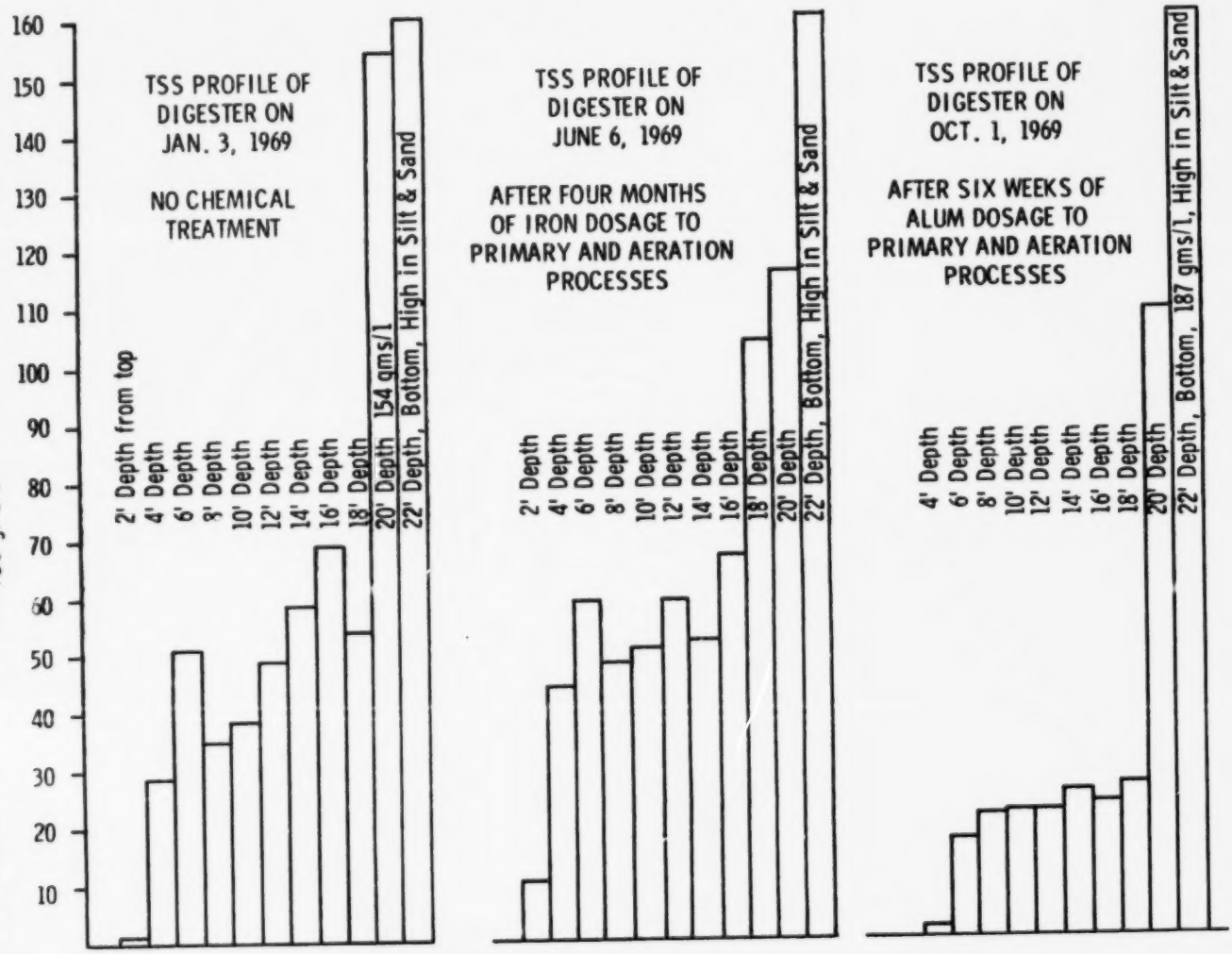

Figure 18.— Solids profiles of digester, showing effect of iron and aluminum dosage to primary and aeration processes.